fundamentals of

radio telemetry

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by MARVIN TEPPER

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FOREWORD

In the multitudes of textbooks on the subject of electronics, radio, electrical engineering, and associated subjects, very little information can be obtained on the subject of telemetry. While it is true that several books have been written about this phase of instrumentation, these previously published books assumed that the reader was fairly well versed on the subject to begin with, and so went into great mathematical and theoretical detail. Undoubtedly these publications have been very useful to design engineers and other experts in the field, but to the average engineer and technician with little or no concept of what a telemetry system consists of, these texts were of very little value.

The author of *Fundamentals of Radio Telemetry* has started his book from the beginning. No assumption is made that the reader has been exposed to this field. Outside of a basic knowledge of electronics no other background is necessary to understand this text.

The importance of telemetry in the research and development of guided missiles and supersonic speed aircraft cannot be over emphasized. Certainly it would be inhuman to ask for volunteers to take a ride in our "one way" missiles, and radio back by voice his observations. Besides, with the amount of data that it is necessary to recover from each flight, it would take several hundred men to transmit simultaneously, meter readings, etc., back to the ground.

It can be readily seen that this is impossible. Through radio telemetry however, several thousands of pieces of information can be transmitted simultaneously so that observers on the ground know every detail and maneuver the missile went through. This information can then be fed into a computer which in turn can give design information to the manufacturers of these missiles, so that ultimately the perfect missile can be produced.

It is no longer astonishing (or is it?), to read the morning newspapers and see that a computer in New York has launched a missile in Florida and successfully guided it to its target. A few short years ago this would have sounded (to the average citizen), like a science fiction novel. Today, it is yesterday's news. Actually the combination of remote-control and telemetry, as well as other instrumentation fields (radar tracking, optical coverage, etc.,), have made this modern-day miracle possible.

Although the government, and private concerns under government contracts, are prime users of telemetry systems, its potential use in industrial and private enterprise should not be minimized. Conceivably in the very near future, a vast telemetry system will be able to cover the nation (and the world, for that matter), and assure safer air travel in faster moving vehicles. It is not too far fetched to believe that data will be recorded during a flight, and given a quick look at on the ground during a fuel or passenger stop, to ensure that all integral working parts are functioning properly, thus assuring a safe continuing journey. More complete data reduction could be performed at central locations which would give information so as to allow the aircraft to be used with maximum safety and minimum "down" time. Currently there is a Civil Aeronautics Administration requirement for the recording of a minimum of five parameters on on a "crash" recorder, for all commercial aircraft that expect to fly in altitudes of 25,000 feet or higher.

These instanced applications of telemetry systems are just a very few usages of an electronic system that is still in its infancy. It would take volumes to give a comprehensive listing of past, present and expected future applications.

As a rule, a telemetry system is a subsystem within a much larger system. For example, to get complete results of a missile test flight, it may be necessary to correlate telemetry information with timing, radar, phototracking, communications and other data, which, each in turn, is a subsystem of an overall instrumentation system. For this reason it is sometimes hard to define where a telemetry system starts and where it ends. For example, a computer could be considered part of a telemetry system, although as a rule it is shared with the other subsystems previously mentioned.

With the publication of this book, it is hoped that the many technicians and students who have regarded telemetry as somewhat of a mystery, will find that mystery solved.

To experts in the various phases of the telemetry system, the humblest apologies are offered for not having covered their particular section in greater detail. To have done so would have defeated the purpose of this book.

WILLIAM GLASS
Engineering Representative
Ampex Corp.

PREFACE

The reason for this book is perfectly simple. Seeking reading material on telemetry, the author was quickly brought to a halt: he found one or two books on the engineering aspects of telemetry, but there was no information on the overall picture. The results of plaguing a few engineers and perusing untold numbers of trade journals and advertising brochures were copious notes and ideas. With them, why not write an article! Surely there were others as interested in the total picture of telemetry! The idea was quickly accepted, but it was soon apparent that the information gathered was far too much for one article, or even for a series of articles, unless the information was watered down. Rather than do that, the author went a step further; you are about to read the end result, a book on telemetry.

This book was written with the idea of explaining the overall picture of telemetry. Too few people realize the entire scope of telemetry. Friends both in and out of the electronics industry, discovering work in progress about telemetry, would invariably ask one question, "What is telemetry about?" At first explanations were difficult: where to start?; how deep should the discussion go? After several discussions it was discovered that most people considered telemetry to almost exclusively concern the missile itself; very few people realized the extent of allied ground equipment. As these discussions continued, the answers became more clear.

It was found that the most satisfactory explanations started with some of the background of telemetry. Then, it was natural to discuss what is measured, and how it is measured and encoded. Transmission from the missile and reception on the ground were easily explained. The decoding of the information was more difficult to make clear, since each manufacturer is sure his methods are the best, and there are many manufacturers! Telemetry in satellites proved to be a most popular topic, and interest was keen and the discussions spirited, particularly when comparing *our* satellites to *theirs*.

From these discussions and questions and answers, with people interested in telemetry, the material for this book was weighed, sifted, and finally written down. No attempt has been made to discuss all the minute details regarding telemetry—the aim was for a general overall picture. By clearing

some of the misunderstandings, and filling in the lack of information, it is hoped that an increased awareness of what constitutes telemetry will result.

If all of the individuals who read this book, together further the progress of the nation's abilities by the smallest amount, the author will be amply rewarded.

MARVIN TEPPER

Malden, Mass.
January 1959

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1. INTRODUCTION TO TELEMETRY

What is Telemetry?

Telemetry might best be introduced by a definition of the word itself. *Tele* is the Greek word meaning "far off," *meter* is the Greek word for "to measure." Combining the two, *telemeter* means "to measure from afar." This aptly describes the science that began by using basic telemetry circuits to measure inaccessible values such as the temperature of an oven, and now produces the complex systems used in guided missiles.

Partly due to the requirements of military security, partly because of the constant advances made in the past few years, there is a general and serious lack of knowledge regarding telemetry. Many people in the field of electronics itself have a limited knowledge of telemetry. To help fill this void, this book presents the fundamentals of the various phases of telemetry.

Lord Kelvin, an English scientist, once stated "If you are able to measure something, then you are in a position to talk about it." This truth is obvious; measurements of any problem must be had before steps to solve it can be taken. As man's scope widened, and he began to tackle problems beyond his immediate environment, telemetry became a necessary development. As far back as 1885, patents were issued in the United States for an electrical telemetering system. In Chicago, a public utility began using one in 1912. This was a wired system, useful for conveying information over long distances, often employing power lines or telephone lines. In the mid-1930's, with the increased knowledge of the higher radio frequencies, balloon-supported transmitters *(radiosondes)* were used to provide weather information.

In the 1940's, World War II spurred all branches of armaments and electronics. Two of the results were rockets and radar. By the end of the war, the Axis was bombarding with V2 rockets and the Allies were retaliating with radio-controlled drone aircraft. The use of high-speed aircraft and missiles accelerated research in telemetry. Flight testing of aircraft utilized various telemetry techniques. One is the use of photographic cameras to record the instrument panel readings. Another method focuses a television camera on the instrument panel so that it transmits video signals to either an accompanying aircraft or the ground station. A third technique uses large banks of multiple-recording oscillographs, capable of indicating as many as 50 variables on a single continuous recording chart. The results obtained, although helpful, were *limited*—they could not always follow rapid changes of information.

Missiles present special problems. Often they are "one shot" affairs. When a missile is to be recovered, shock-mounted cameras are used. Some missiles, or parts of a missile, are parachuted to recovery intact, and much information is preserved. But by far the most satisfactory answer to obtaining information from missile flights is to employ telemetry.

In the early days of missile testing, carrying the missile under the wings of a high-speed aircraft, using shock-resistant cameras, photo tracks recorded on film, and wind-tunnel experiments, were methods used to gather information. Under non-recoverable, high-altitude, high-speed conditions, some of these methods became obsolete and radio telemetry came into prominent use.

The basic concept behind radio telemetry is shown in Fig. 1-1. A radio signal containing many channels of information regarding conditions both inside and outside the missile emanates from the missile in flight. This

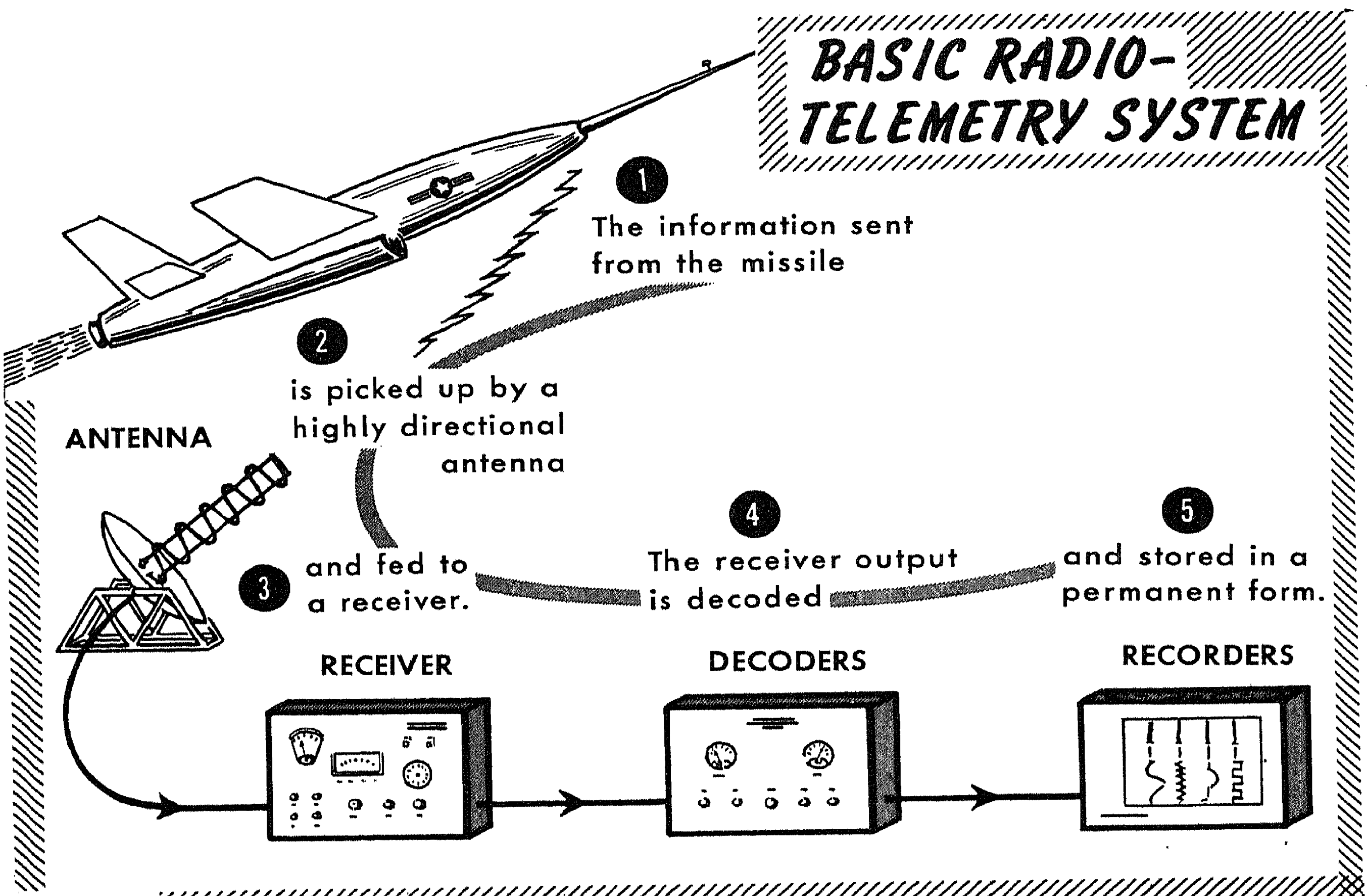


Fig. 1-1

signal is picked up by a specially designed antenna, tuned in on a receiver, detected, and broken down into specific channels of information. Each channel is applied to a device that produces a permanent record.

Telemetry offered many advantages which were quickly put to use. In aircraft testing, it relieves a pilot of copying information from his instruments, so that he can concentrate on flying. This, of course, increases to a great degree the pilot's safety, and squeezing an additional observer into the crowded pilot's quarters is no longer necessary. With the information being transmitted by telemetry, remote control has been made practical, particularly in possibly dangerous situations. Monitoring critical functions

during a flight permits a finer control of the test, thus reducing the number of flights required. By tracing the telemetered information on reproducible forms such as paper charts or magnetic tapes, the information can be checked at more convenient times and places.

Radio control, often called missile guidance, is a form of telemetry. However, the discussion in this book will be primarily of the telemetry used to transmit data. This transmitted information, in the form of measurements, is evaluated and used for furthering the progress of the particular program under study.

Telemetry Standards

During and after World War II, the Office of Scientific Research and Development (OSRD) sponsored much telemetry research. As the tempo of missile research stepped up, various telemetry standards were often established. The committee on guided missiles of the Research Development Board (RDB), Department of the Defense, recommended a set of standards that, with some changes and additions, were approved. The latest revisions were made by the Inter-Range Telemetry Working Group, and presented to the parent Inter-Range Instrumentation Group. As a result, telemetry standards are often referred to as either RDB, IRTWG, or IRIG standards.

An understanding of some of the more important basic standards is essential to an understanding of telemetry. One IRIG standard that is common to all telemetry systems is the r-f carrier frequency band, which is presently 216 to 235 mc. It is planned that this band will be replaced by 1970, and all activity will be handled in a segment of the 1300-mc band, the exact bandwidth to be announced later. Microwave transmissions take place between 2200 and 2300 mc, using frequency modulation (FM) and phase modulation (PM).

In the FM-FM or FM-PM system, various methods are used to enable the r-f carrier to carry more than one signal. Eighteen different channel frequencies can be applied to modulate the r-f carrier; they may be applied either one at a time or, under the proper circumstances, all at once. These 18 frequencies are *subordinate carrier frequencies,* called *subcarrier* frequencies. Subcarrier frequencies are in turn frequency-modulated by a source of information, as will be explained later.

The 18 subcarrier channels may be likened to 18 doorways of different width through which information may pass. The width of Channel 1 as set by the standards is 30 cycles above or below the center frequency of 400 cycles. The value of 30 cycles is determined by the standards, which call for a deviation of ±7.5% of the center frequency.

To keep the ~~lowest~~ highest signal-to-noise ratio, a modulation index (deviation ratio) of five was chosen. This is shown in Channel 1 by dividing the

30-cycle deviation by 5 and finding 6, which represents the frequency, in cycles per second, at which applied information can modulate Subcarrier Channel 1. A modulation index lower than five may be used at the expense of the signal-to-noise ratio. A modulation index of unity (1) would permit all 30 cycles of information to be passed. However, the signal-to-noise ratio would be low, severely handicapping the resultant output signal. In addition to possible distortion, another difficulty with a modulation index of unity, where the full deviation would be used, is the probability of the information of each channel overlapping, producing "cross talk." Figure

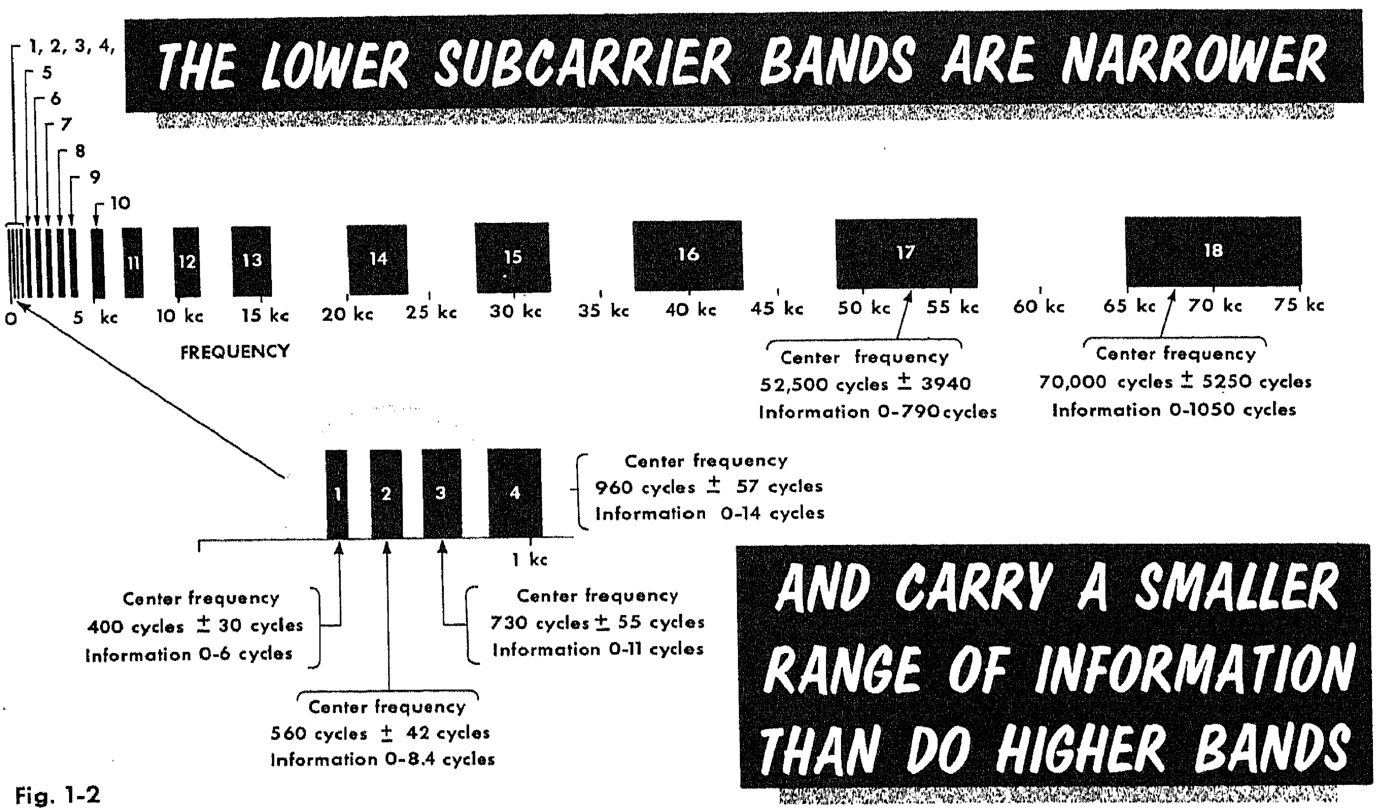


Fig. 1-2

1-2 shows how the bandwidths increase with increasing channel frequency. For full details of the complete channel frequencies, deviation limits, and standard information-carrying capabilities of all channels, see the table.

The table indicates that, as the frequency of each succeeding channel increases, the frequency by which the channel may be modulated increases. The modulating frequency of Channel 1 is six cycles, that of Channel 18 is 1050 cycles. Thus Channel 18 may be used to convey information changing at a maximum rate of 1050 cycles. Slow variations in information are applied to the lower-frequency channels. To allow the subcarrier channel to carry higher information frequencies, the deviation limits of a subcarrier channel may be increased. Doubling the deviation doubles the frequency of information that can be handled by a channel. As a result, the last five channels, 14 through 18, may be used with an increased value of 15% deviation limits. For identification, these channels are labeled A through E. When any of

these channels are used, sidebands will cross into adjacent channels, resulting in the necessary omission of other channels. Note in the table that the use of Channel A or Channel E results in only two other channels being omitted, whereas Channels B, C, or D require the omission of four

SUBCARRIER BANDS

Band	*Center Frequency (cps)*	*Lower Limit (cps)*	*Upper Limit (cps)*	*Maximum Deviation (percent)*	*Frequency Response* (cps)*
1	400	370	430	±7.5	6.0
2	560	518	602	"	8.4
3	730	675	785	"	11.
4	960	888	1,032	"	14.
5	1,300	1,202	1,398	"	20.
6	1,700	1,572	1,828	"	25.
7	2,300	2,127	2,473	"	35.
8	3,000	2,775	3,225	"	45.
9	3,900	3,607	4,193	"	59.
10	5,400	4,995	5,805	"	81.
11	7,350	6,799	7,901	"	110.
12	10,500	9,712	11,288	"	160.
13	14,500	13,412	15,588	"	220.
14	22,000	20,350	23,650	"	330.
15	30,000	27,750	32,250	"	450.
16	40,000	37,000	43,000	"	600.
17	52,500	48,560	56,440	"	790.
18	70,000	64,750	75,250	"	1,050.
A**	22,000	18,700	25,800	±15	660.
B	30,000	25,500	34,500	"	900.
C	40,000	34,000	46,000	"	1,200.
D	52,500	44,620	60,380	"	1,600.
E	70,000	59,500	80,500	"	2,100.

*Frequency response given is based on maximum deviation and a deviation ratio of five. (See text for discussion.)

**Bands A through E are optional and may be used by omitting adjacent bands as follows:

Band Used	Omit Bands
A	15 and B
B	14, 16, A, and C
C	15, 17, B, and D
D	16, 18, C, and E
E	17 and D

other channels. The use of Channel E permits conveying of information changing at a rate twice that of Channel 18, or 2100 cycles.

The PDM-FM or PDM-PM system, to be explained in more detail later, enables the r-f signal carrier to carry more than one information channel. This is accomplished by dividing the *time* the carrier is on the air into known amounts, each amount representing a different channel of information. The information is converted to a value of time, then the r-f carrier is turned on to transmit a pulse of energy for the length of time representing the value of the information. As shown in Fig. 1-3, a pulse duration of

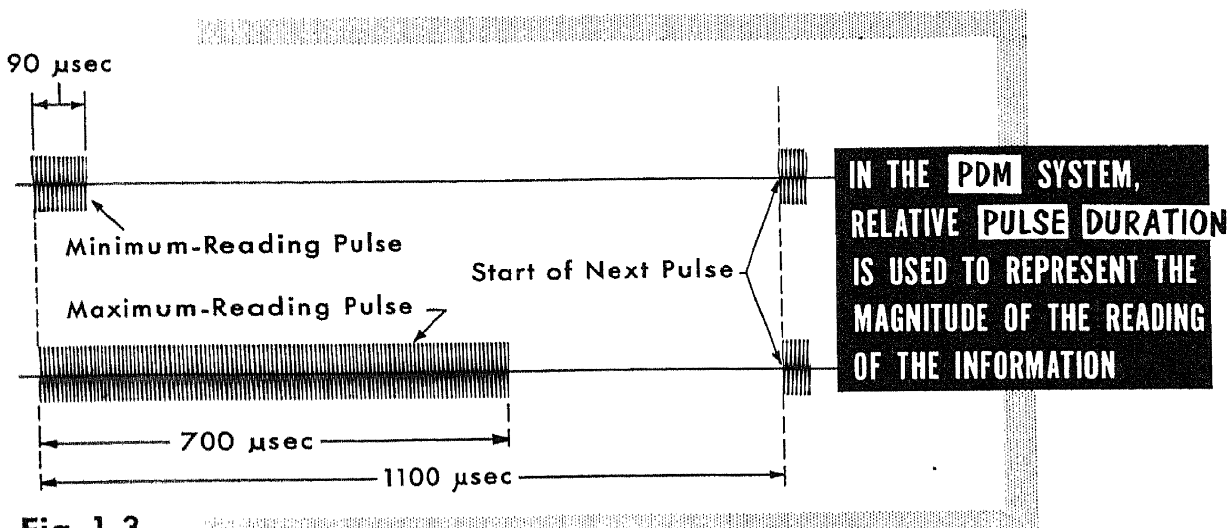


Fig. 1-3

90 microseconds (μsec) represents a minimum-information reading; a pulse duration of 700 μsec represents a maximum-information reading. For example, 90 μsec might represent a minimum-information level of the output of an instrument say, zero pounds per square inch of pressure. The 700 μsec might represent a maximum-information level of 100 pounds per square inch. An intermediate pressure, say, 50 pounds per square inch, would then result in a pulse duration of 395 μsec.

These pulses of information are sent in specific numbers, 900 per second. This could represent 43 information channels sampled 20 times per second. Two additional channels are transmitted with no information to identify the beginning and end of each group of information.

This synchronizing information is detected on the ground and assures that the information is recovered in the proper sequence. This means that the pulse representing information channel No. 1 always follows the synchronizing pulse and the pulse preceding the synchronizing information is the last information channel (43 in the example given above).

It is important to remember that telemetry is not a specific system of any one type. Most often, it is a combination of various methods designed to meet a specific problem.

2. TELEMETRY INSIDE THE MISSILE

Basics of Transducers

The reason for using a telemetering system is to convey measured information over large distances. The essential unit in the system, therefore, is the device that measures the desired information. The measuring device is often called a *pickup*, or more properly a *transducer*. There are various definitions of the word transducer; "a device actuated by power from one system supplying power to a second system," "a device used to convert energy from one type to another," etc. The transducer, then, as used in telemetry, creates an electrical change for an equivalent mechanical change. Perhaps the best known transducers are microphones, where variations in air pressure result in equivalent electrical variations.
Some of the items that rocket engineers must measure to obtain desired information are launching statistics, acceleration, fuel pressure, displacement, altitude, air speed, temperature, shock, vibration, stress, strain, rate of climb, pitch, yaw, position, fuel flow, air flow, force, weight, light or emissivity, thrust, humidity, operation of control surfaces, motion, and various voltages and currents.

In order for the transducers to convert mechanical changes to electrical changes, some of the required measurements, such as pressure and stress, must be converted to mechanical variations so that they may be applied to

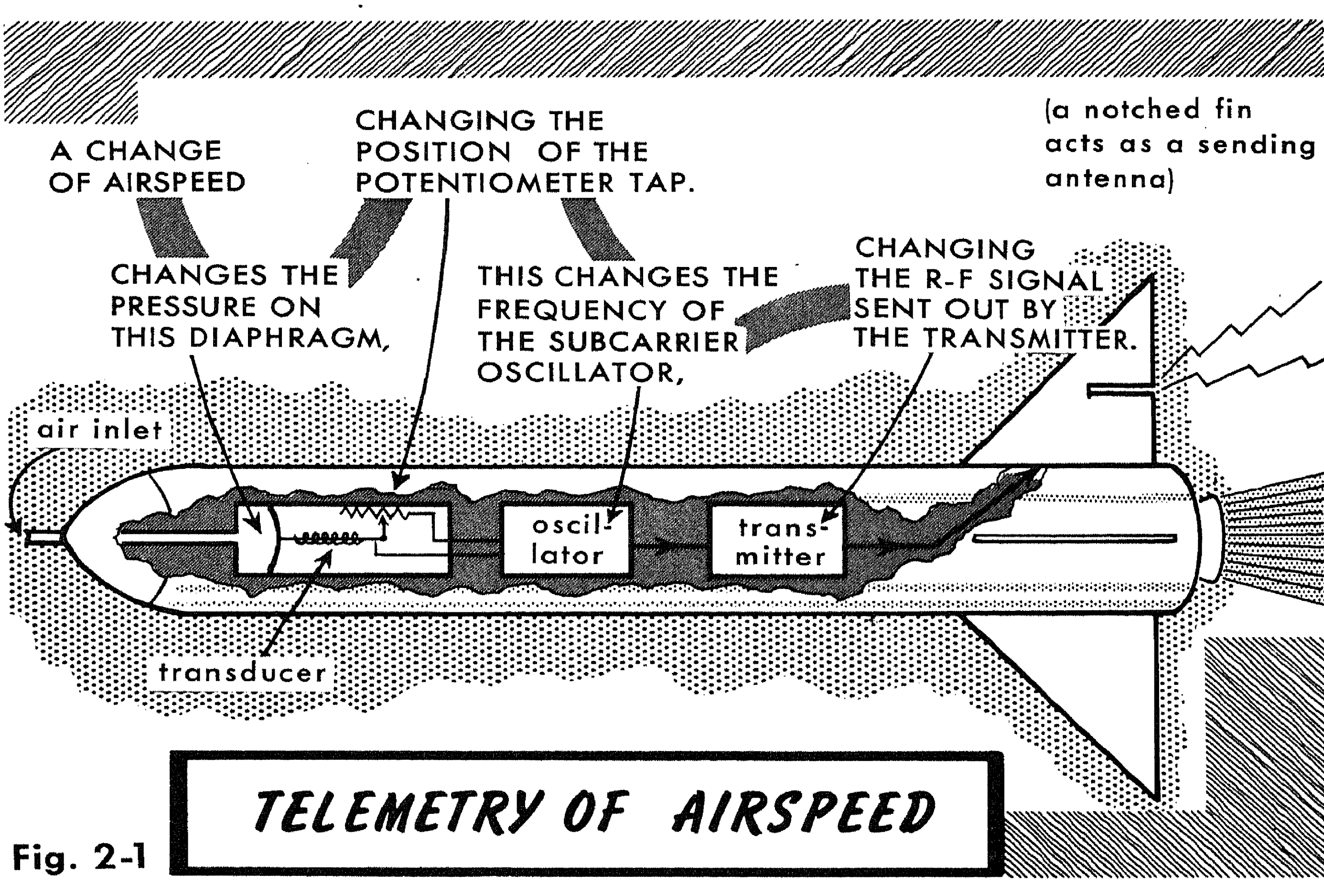


Fig. 2-1

the transducers. The mechanical-conversion devices vary with the ingenuity of the design engineer. Some use flexible bellows that expand or contract with changes in pressure. Another device is direct mechanical linkage to a moving part, allowing the movement to move a tap on a potentiometer. A basic version of a mechanical change being converted to an electrical change is shown in Fig. 2-1. Here the air speed produces a pressure that moves a diaphragm, which in turn moves the tap on a potentiometer. The voltage at the tap of the potentiometer alters the frequency of an oscillator (as will be explained later), and the signal transmitted provides information regarding the air speed.

The basic principles of transducer design shown in Fig. 2-2 are varying resistance, varying capacitance, and varying inductance. There are also transducers using photovoltaic or photoconductive devices. Transducers

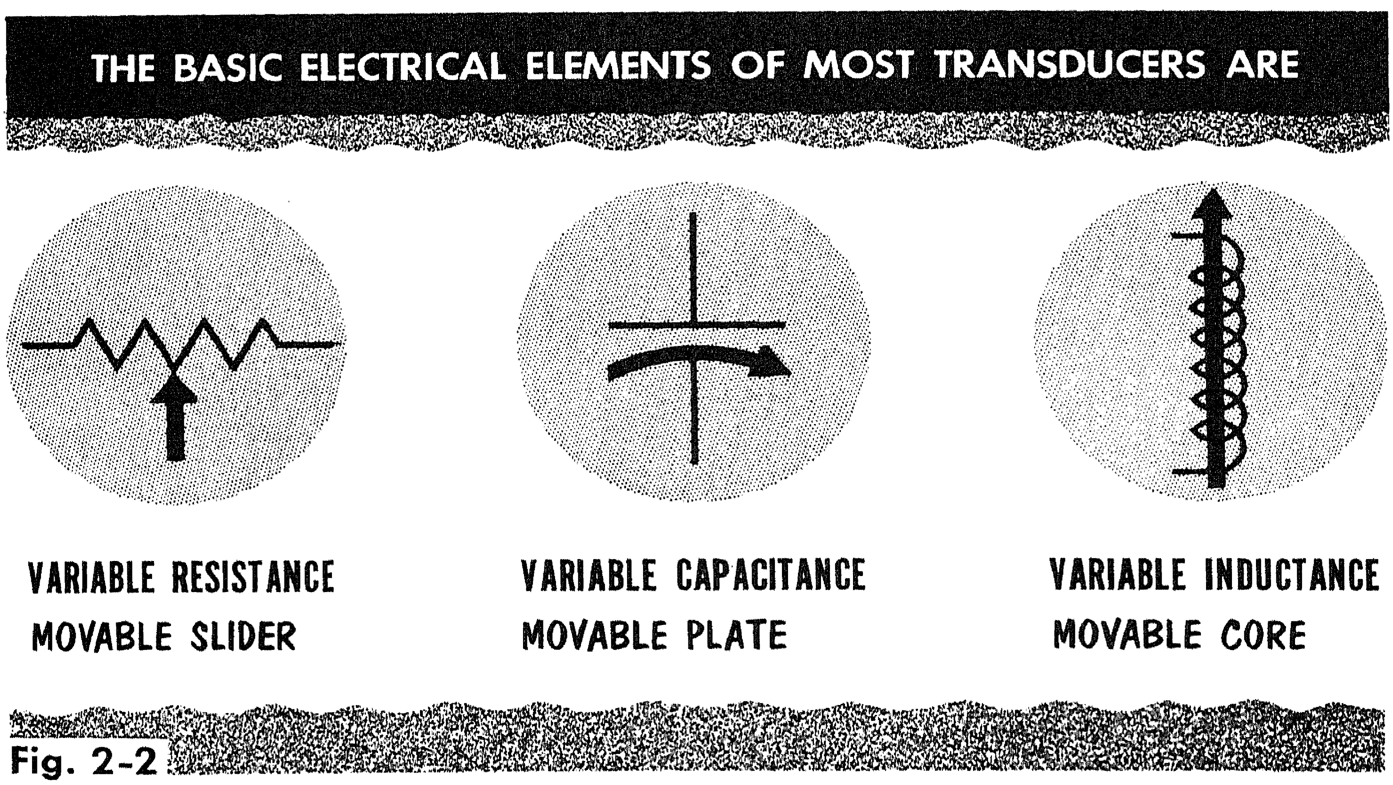


Fig. 2-2

may be classified into generating or nongenerating types. The generator-type transducers, capable of providing a self-generated output voltage, are the piezoelectric, photovoltaic, magnetic, and thermoelectric types. Non-generating-type transducers, which modulate an oscillator, are the variable-capacitance, variable-resistance, and variable-reluctance types. Although some principles are best suited for specific purposes (such as the phototransistor for measuring illumination), most of the different measurements are made using the basic principles of varying resistance, capacitance, and reluctance. For this reason, our discussion of transducers will place emphasis on resistive devices, capacitive devices, and inductive devices.

The requirements encountered in missilery are extremely severe. The basic requirements may be summarized in four categories:

(1) *Packaging*. The equipment must be built in the smallest possible space with the least weight.

(2) *Reliability*. The equipment must operate in extreme temperature ranges with high levels of vibration and shock.

(3) *Accuracy*. The equipment must measure to close tolerances, often to 0.5% or better.

(4) *Maintenance*. The equipment must be easy to service, and have the least possible number of adjustments.

Modular construction (replaceable plug-in units) is preferred.

Resistive Transducers

Resistive transducers, as shown in Fig. 2-3, are essentially of three types:

(1) Potentiometers

(2) A length of resistance wire, changed in value by stress or strain (strain gage).

(3) A resistor changed in value by changes in temperature.

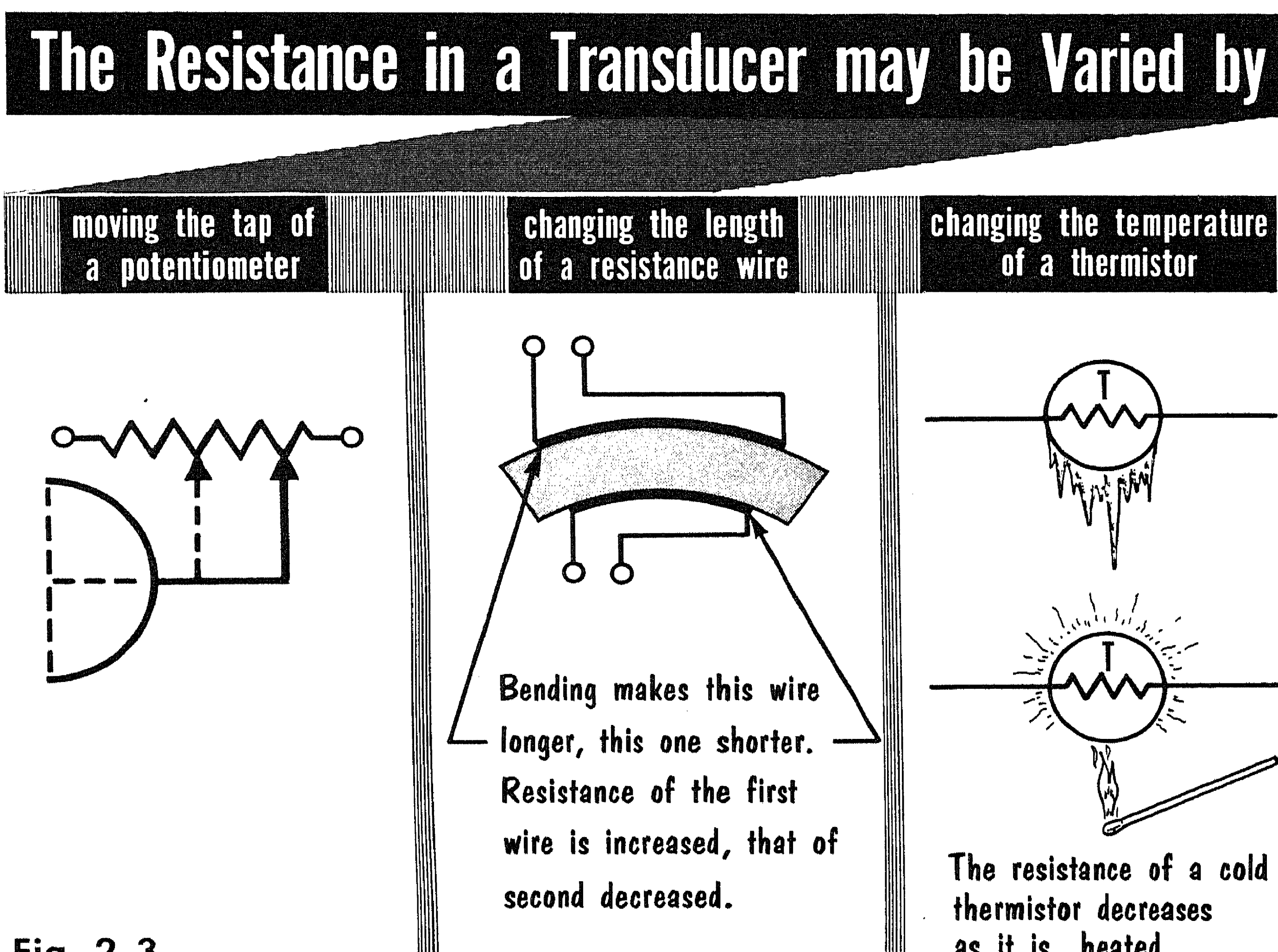


Fig. 2-3

Potentiometer-type transducers depend upon a linear or rotary motion to move the wiper arm. Placing the potentiometer across a voltage source permits a variable output voltage between one end of the potentiometer winding and the variable wiper arm. A major advantage of a potentiometer-type transducer is its ability to directly control an oscillator specifically designed to have its frequency altered by voltage changes. The voltage source placed across the potentiometer may be relatively high, providing a high-voltage output.

To transfer the application of pressure to a mechanical motion, various devices are used. Figure 2-1 showed how air pressure flexes a diaphragm,

A BELLOWS-TYPE PRESSURE TRANSDUCER

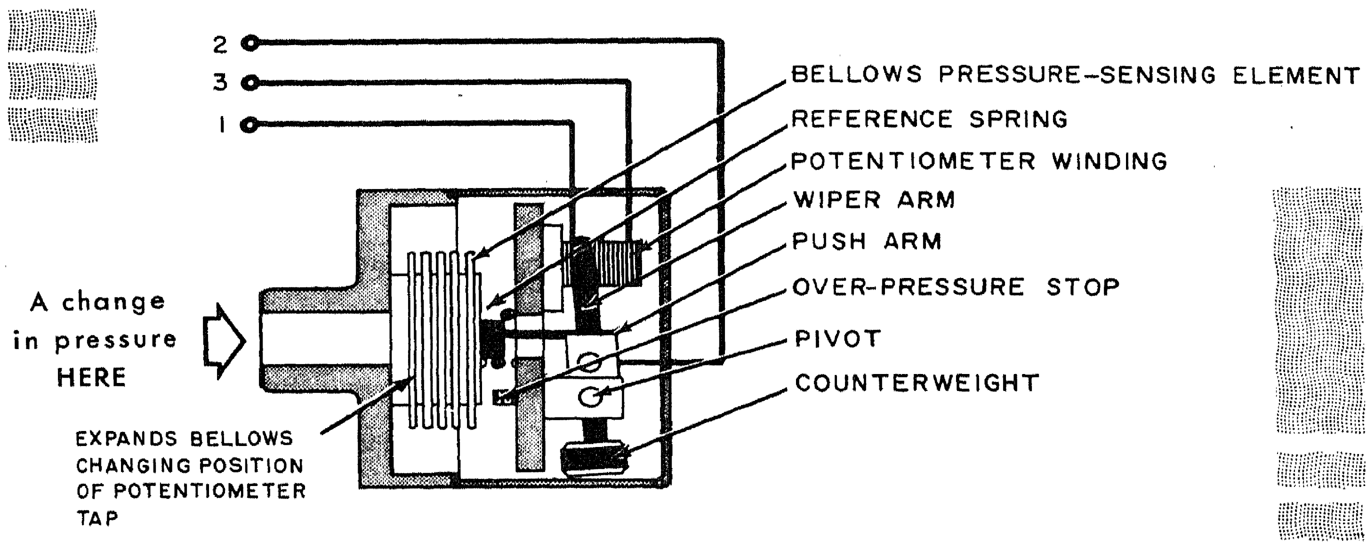


Fig. 2-4

which in turn varies a potentiometer. For more accurate measurements, an expandable bellows (Fig. 2-4) may be used.

To convert varying pressures to varying values of voltage, a bellows-operated transducer that transfers the changing pressure to variations in the position of a potentiometer wiper arm is shown. Note the counter weight at the end of the wiper arm that acts to reduce the instrument's sensitivity to changes in acceleration. It is not visible on the diagram, but the wiper arm rotates on ball bearings for reduction of friction.

Another method of converting pressure to mechanical motion is the Bourdon tube, invented by Eugene Bourdon in Paris in 1847. First designed as a pressure gage, the Bourdon tube is a thin, hollow, elliptical tube in a circular shape, with one end sealed. Applying pressure to the open end of the tube causes it to try to straighten itself (Fig. 2-5). This principle operates the noisemaker seen at children's parties. The child blows into

THE BOURDON-TUBE TRANSDUCER

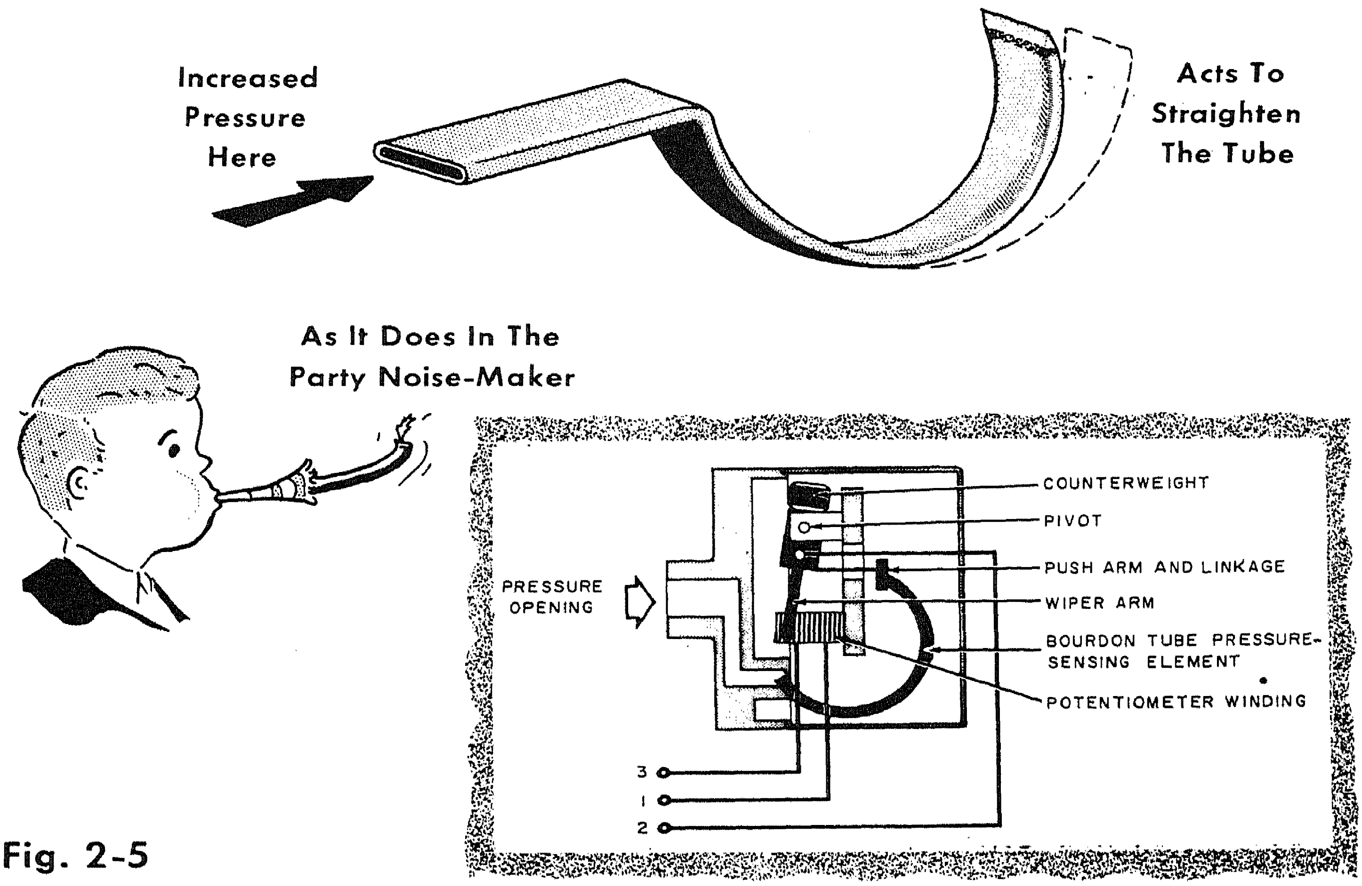
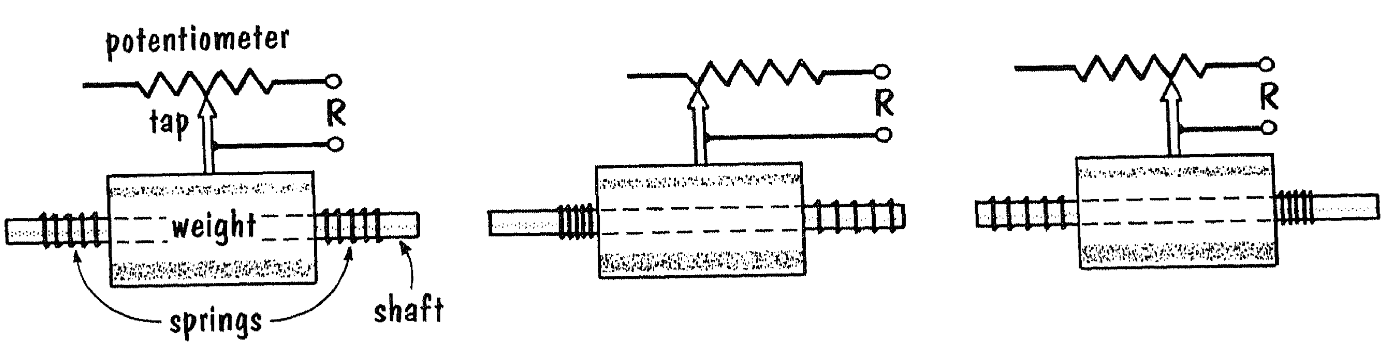


Fig. 2-5

HOW AN ACCELEROMETER WORKS



when missile is standing still or moving at a constant velocity, the weight is kept at the center of the shaft by the springs. The resistance at the tap is medium.

When missile speeds up, the weight moves back on the shaft. The resistance at the tap is high.

When the missile slows down the weight moves forward on the shaft. The resistance at the tap is low.

DIRECTION OF FLIGHT

Fig. 2-6

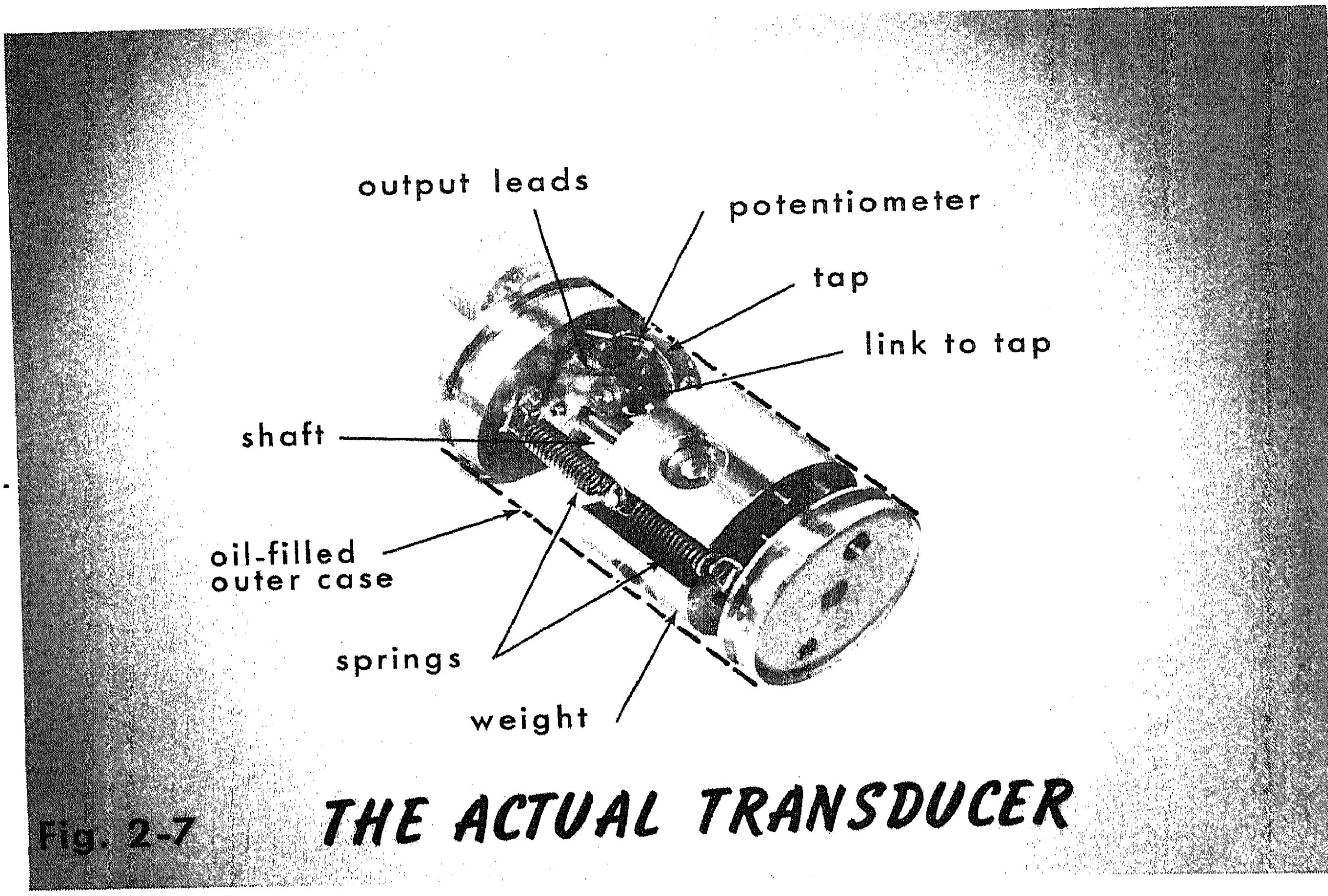
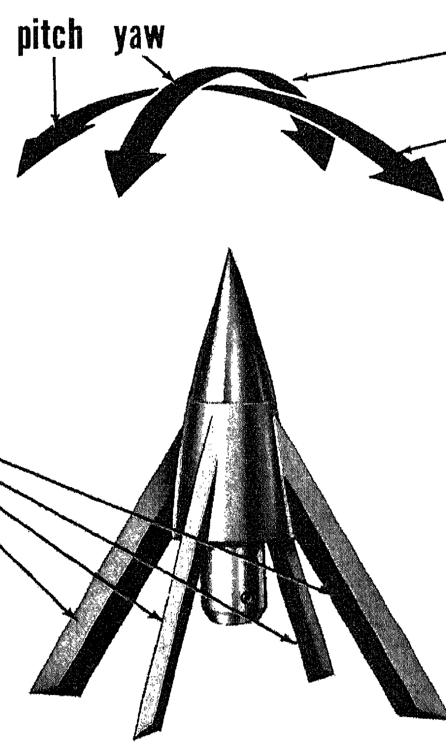


Fig. 2-7 THE ACTUAL TRANSDUCER

A TRANSDUCER THAT INDICATES PITCH AND YAW



The transducer installed on a Redstone missile

Fig. 2-8

a rolled-up flat paper tube which is sealed at one end, causing it to roll out straight as it opens. A transducer using this method of varying a resistance is also shown in Fig. 2-5.

An accelerometer transducer, as the name implies, measures acceleration. Acceleration is usually sensed by a method of measuring the movement of a mounted weight, or mass, as shown in Fig. 2-6. One type (Fig. 2-7) uses an oil-dampened spring-supported linear-ball-bushing-mounted mass that actuates a potentiometer-wiper arm as it moves along a shaft.

A transducer employing two potentiometers to measure pitch (angle of attack), and yaw (angle of sideslip), is shown in Fig. 2-8. The unit is swivel-mounted, allowing it to be placed directly in the air-stream flow and providing dual-flow direction indication. A typical installation of this type of transducer is also shown.

Varying the cross-section area of a length of wire will vary its resistance; a thin wire offers higher resistance than a heavy wire. One type of pressure-reading transducer contains a bellows to which is connected a cantilever beam. Four flat coiled resistors are mounted so that, as the cantilever beam is moved by pressure on the bellows, two of the resistor coils are stretched, and the other two are compressed. The resistor wires that are stretched have their resistance increased, the resistor wires that are compressed have their resistance decreased. By connecting the four resistors in a bridge circuit, an output is obtained that varies linearly with the pressure applied. By applying a known pressure the bridge can be balanced, and the transducer then indicates either a rise or fall in the pressure applied.

Compact mounted resistors are transferable to the surface being tested. Using resistance wires of Constantan, Nichrome V, platinum, etc. bonded to the surface, any change in temperature will vary the resistance. A typical installation used to measure temperature is shown in Fig. 2-9. The resistors used to measure stress, strain, or temperature are usually inserted as one

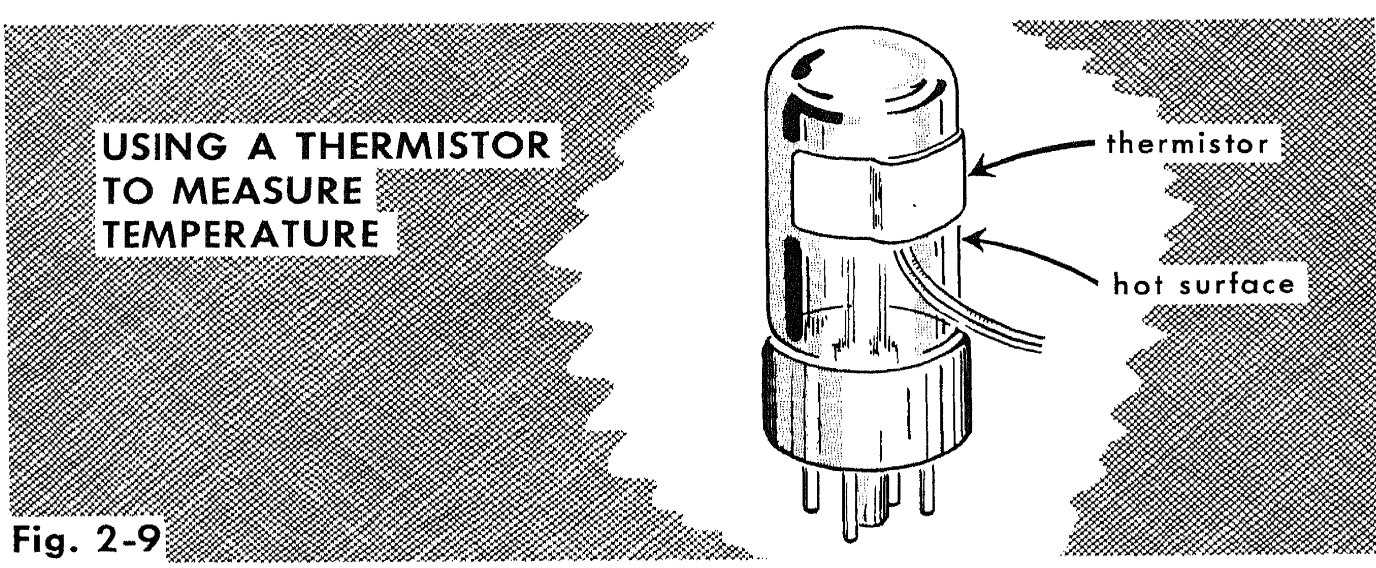


Fig. 2-9

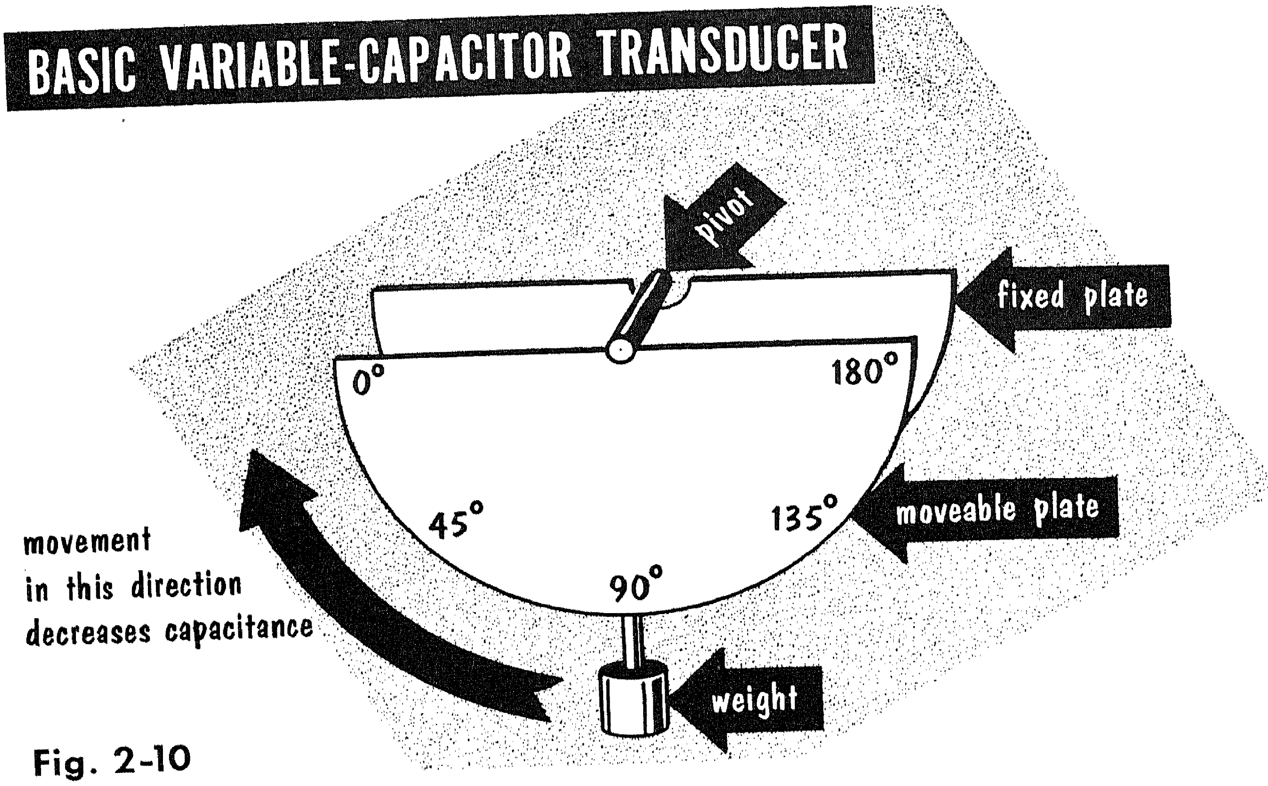
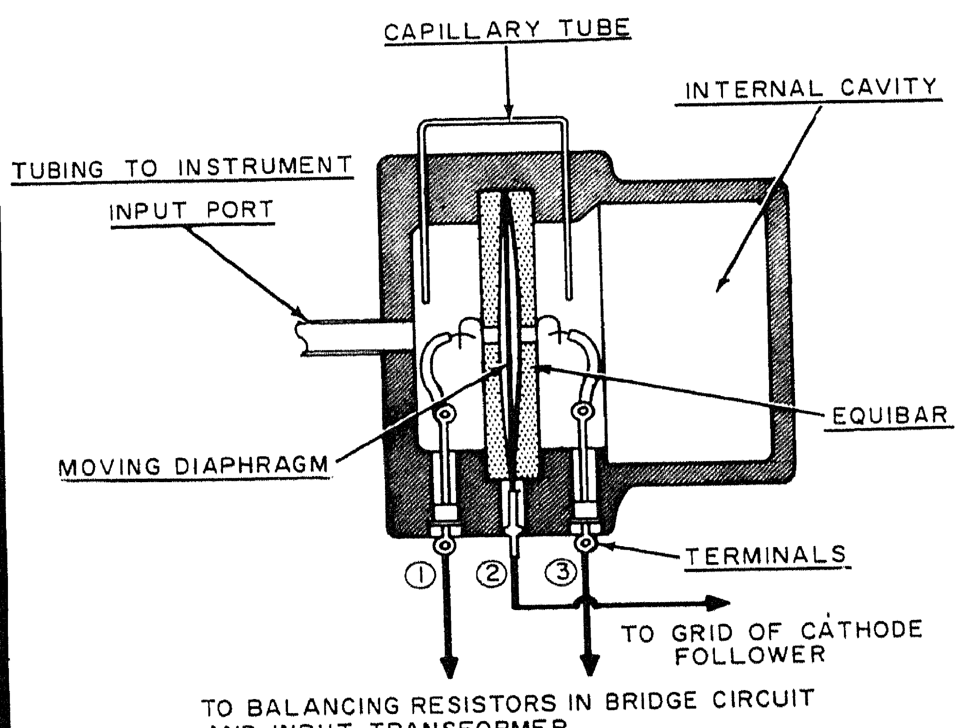


Fig. 2-10

arm of a bridge circuit. It is often necessary to measure many points for temperature or stress. This simplifies things because only one bridge circuit need be used, and each indicating resistor may be switched in place in turn.

A thermistor is a nonlinear resistor, meaning that it changes in resistance value as its temperature changes. This is due to special materials whose



Pressure-Sensitive Transducer Used For Vertical-Speed Measurements

Fig. 2-11

resistance decreases as the temperature increases, and vice versa. By using a thermistor as one leg of a bridge circuit, any changes in temperature are immediately apparent by a change in the resistance of the thermistor.

Capacitive Transducers

A basic capacitor consists of two conducting plates separated by an insulating dielectric. To vary the capacitance, we may vary any or all of the following: the area of the plates, the distance between the plates, the nature of the dielectric. Capacitive transducers operate on the basis of varying any one or more of these three variables. Placing one capacitor plate in a fixed position and the other on a pivot, causes any movement to vary the area between the two plates, thus varying the capacitance. Keeping one plate of a variable capacitor fixed, the other plate can be arranged to rotate with changes in angular position (Fig. 2-10). The varying-capacitance output can be referenced for the degree of swing. Capacitive transducers are excellent for use in FM-oscillator circuits. With the capacitance placed directly in the tank circuit, the varying transducer will automatically frequency-modulate the oscillator.

A capacitive transducer that measures vertical speed is shown in the diagram of Fig. 2-11. The instrument uses an "Equibar" pressure sensing element as a capacitive voltage divider in an AC bridge circuit. A thin metal diaphragm held in place between two electrodes is moved by the pressure applied to the input port. The pressure applied to the input port causes a pressure drop in the capillary tube connecting the input port to the internal cavity. This results in the pressure in the internal cavity being applied to the diaphragm in a direction that reinforces the pressure in the input port. The variations between the diaphragm and the two sides of the equibar result in a varying capacitance.

Inductive Transducers

Inductive transducers are of two types: voltage-generating and variable-reluctance devices. Variable reluctance-type transducers operate on the principle of holding the coil intact and varying the core, or holding the core intact and varying the coil. Placing the coil as a part of the tank circuit of an oscillator permits direct changes in reluctance to be transmitted as direct changes in frequency.

A variation of the Bourdon tube principle is shown in Fig. 2-12, where a hollow tube, flattened, twisted, and sealed at one end, is applied to an armature. Applying increased pressure to the tube causes it to straighten, twisting the armature in one direction. Reducing the applied pressure causes the tube to twist further, moving the armature in the opposite direction. The varying armature varies the reluctance of a transformer. A cutaway view of a similar unit and the way it acts to shift the frequency of a subcarrier oscillator are shown in Fig. 2-13.

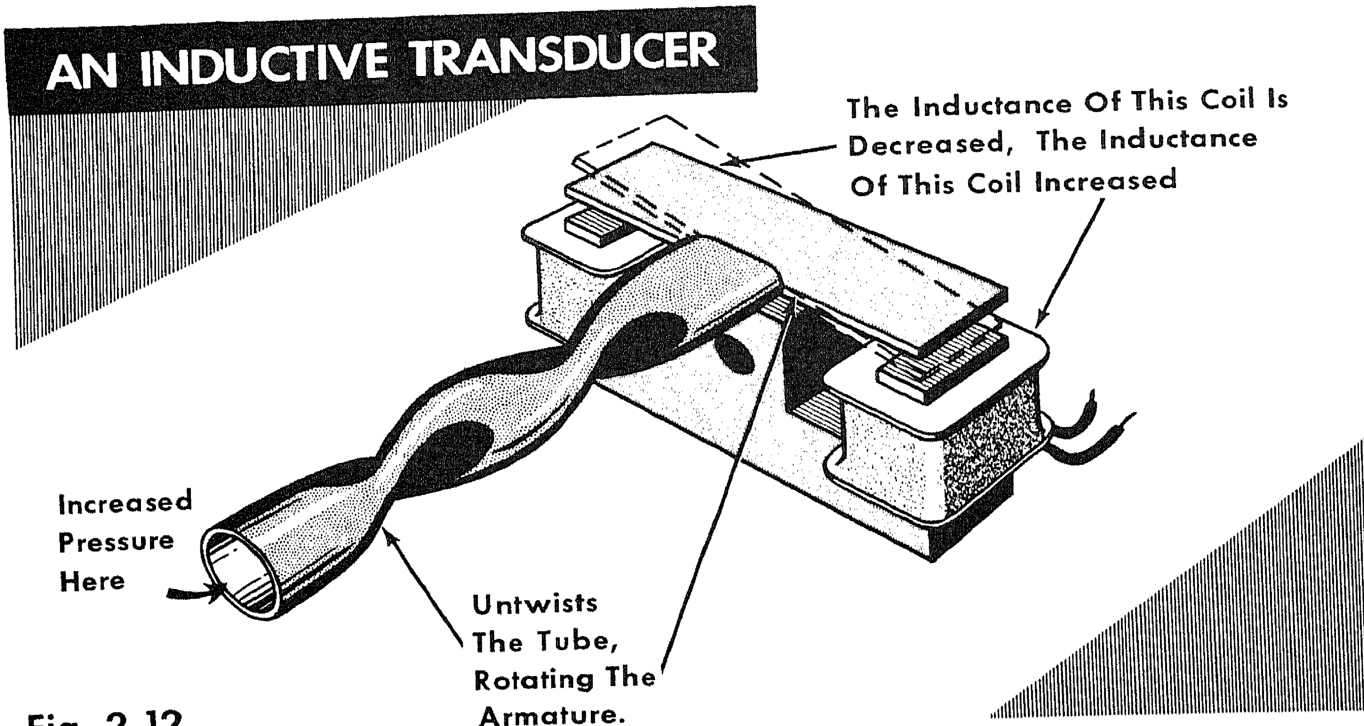


Fig. 2-12

The nature of certain materials indicates specific uses for a given transducer. A thermocouple is a junction of two dissimilar metals; heat applied to the thermocouple junction develops a small voltage. The value of this

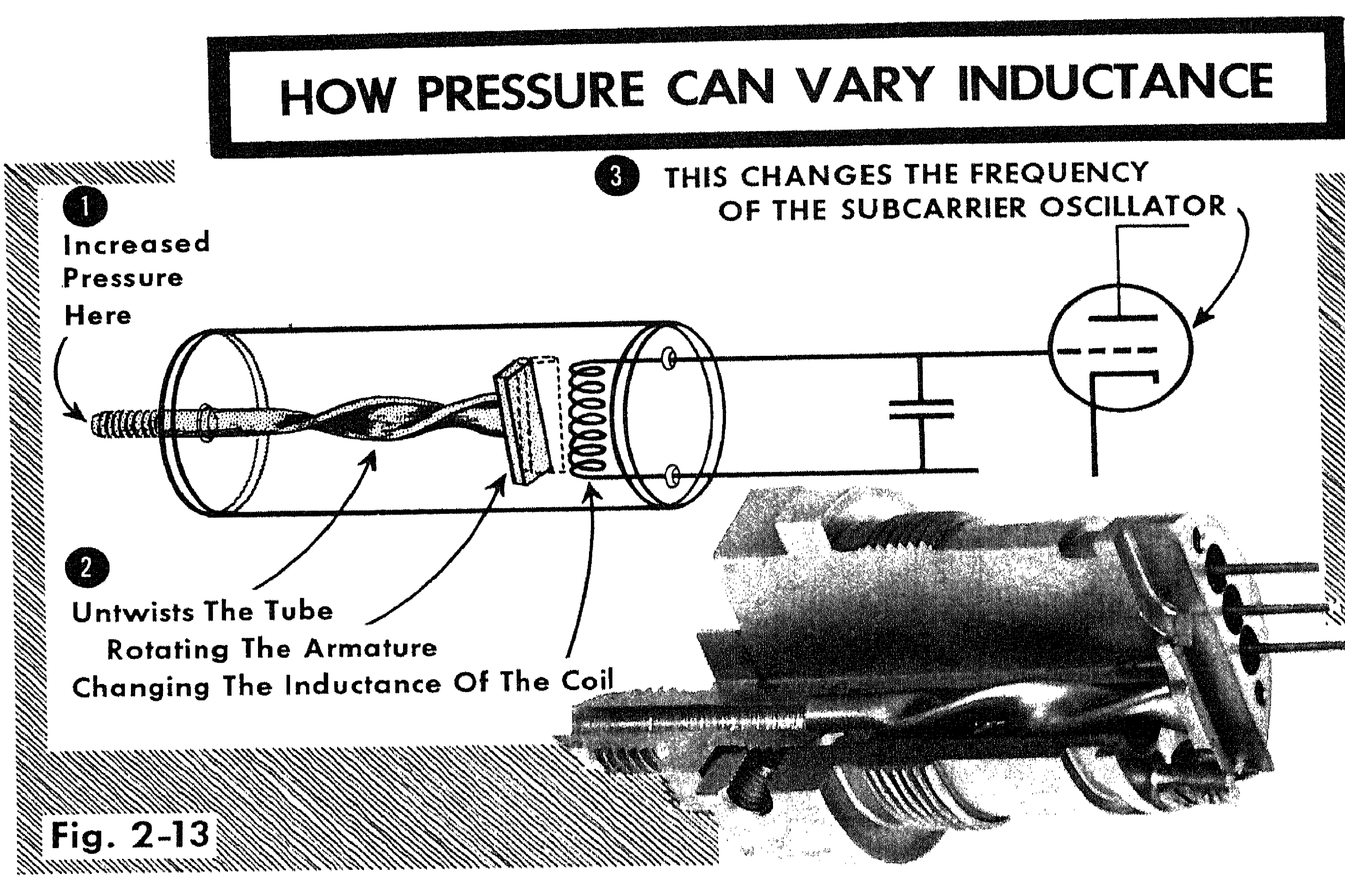


Fig. 2-13

output is proportional to the temperature. Preamplifiers are required since thermocouple outputs average from as low as 3/4 of a millivolt to 5 millivolts. To measure light intensity, a phototransistor or other light-sensitive device, such as a selenium cell, may be used.

Subcarrier Oscillators

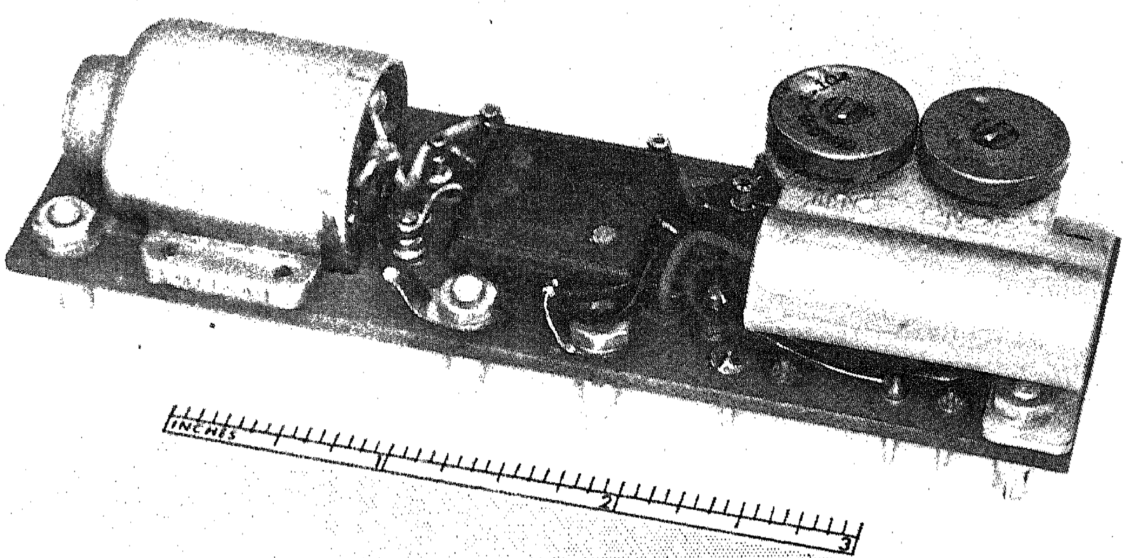
The subcarrier oscillator is a low-frequency oscillator that conveys the information gathered by the transducer. The frequencies, as listed in the table in Chapter 1, vary from an audio frequency of 400 cycles to as high as 70,000 cycles. The subcarrier frequency is then applied to modulate a high-frequency R-F transmitter, as already shown in Fig. 2-1. The IRIG subcarrier frequencies can carry varying degrees of intelligence, depending upon the frequency of the channel selected. The higher the channel frequency the higher the frequency of the information it can carry. The information reproduced by the transducer at the point being measured may vary from zero to a maximum of 2100 cycles. This varying information is used to modulate the subcarrier oscillator. The type of modulation used may be Amplitude Modulation (AM), Phase Modulation (PM), or Frequency Modulation (FM). Frequency modulation of the subcarrier oscillator is most frequently used at present.

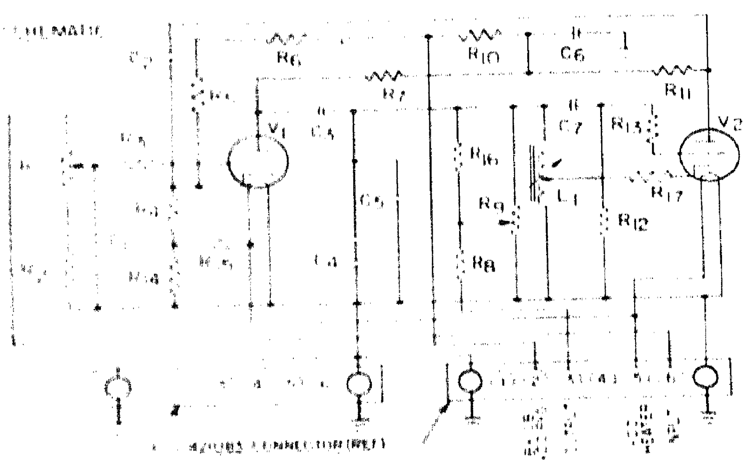
The information to be carried by the subcarrier oscillator may not at all times be that of the transducer. For example, consider monitoring the frequency of a 400-cycle power source that may vary plus or minus 10 cycles. This may be accomplished in several ways:

(1) Have the 400-cycle source modulate the subcarrier oscillator directly on Channel 15.
(2) Have the 400-cycle signal beat against an accurate low-frequency signal such as 450 cycles, and have the difference frequency, which can vary from 40 to 60 cycles, modulate the subcarrier oscillator directly on Channel 10.
(3) Have the difference frequency of 40 to 60 cycles detected and converted to an equivalent d-c voltage varying at a rate of less than 1 cycle. This may be used to modulate the subcarrier oscillator directly on Channel 1.

Of the three possible means of monitoring the 400-cycle power source, the third is the best in that it frees a higher-frequency channel, which might then be used to measure fast-changing variables that may not be handled in the same manner. However, each succeeding step reduces the need for a higher-frequency channel at the added expense of additional equipment. All these factors must be kept in mind.

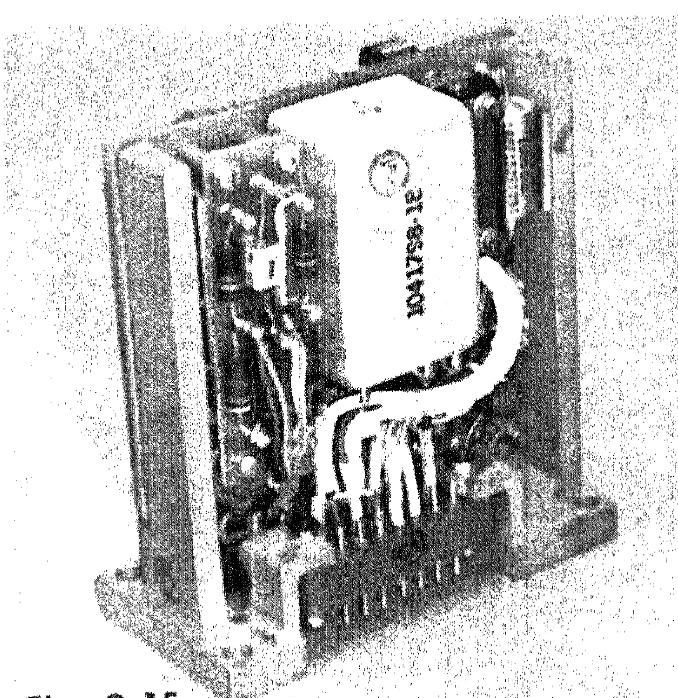
A subcarrier oscillator requires that the modulation vary the frequency linearly. It must have high stability, low drift, and low distortion. Since space and weight are important considerations, simple basic circuits are often used. To aid in achieving these goals, high-grade, close-tolerance components are used throughout the equipment. Various methods may be





VOLTAGE-CONTROLLED OSCILLATOR

Fig. 2-14



TRANSISTORIZED R-C PHASE-SHIFT OSCILLATOR

Fig. 2-15

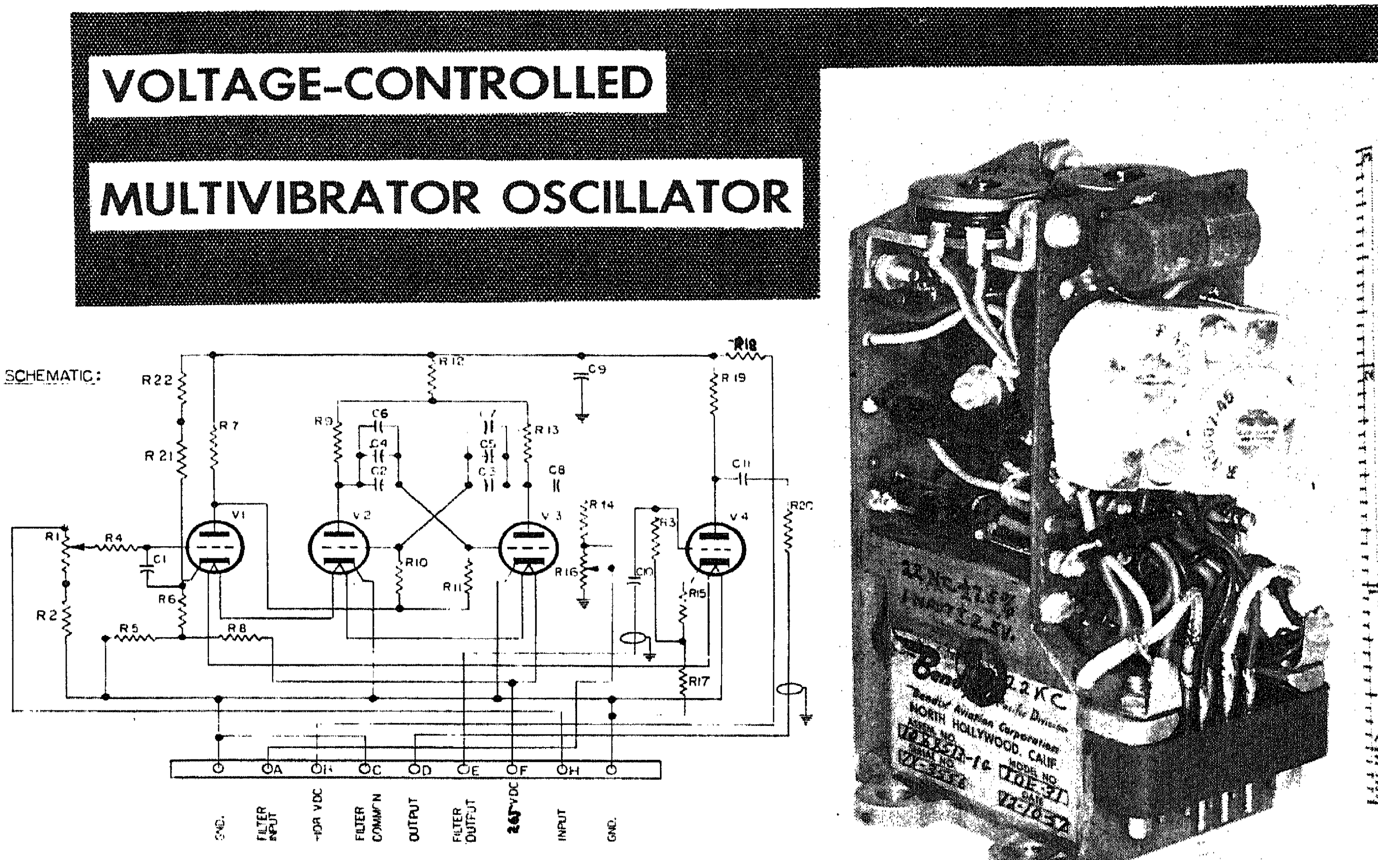


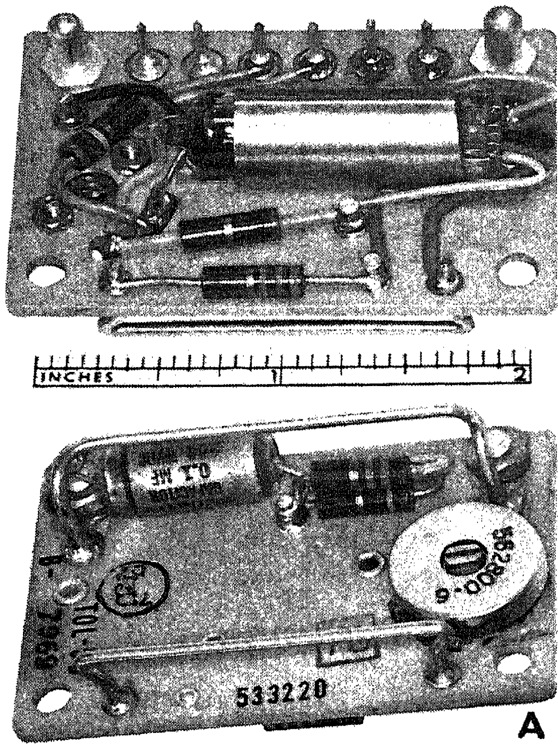
Fig. 2-16

used to check frequency drift. The simplest is to remove, for an instant, the input to the subcarrier oscillator. It then oscillates at a known specific frequency. Another method is to apply a calibrating voltage to the subcarrier oscillator to produce a known specific frequency. There are three types of oscillator circuits in general use as subcarrier oscillators:

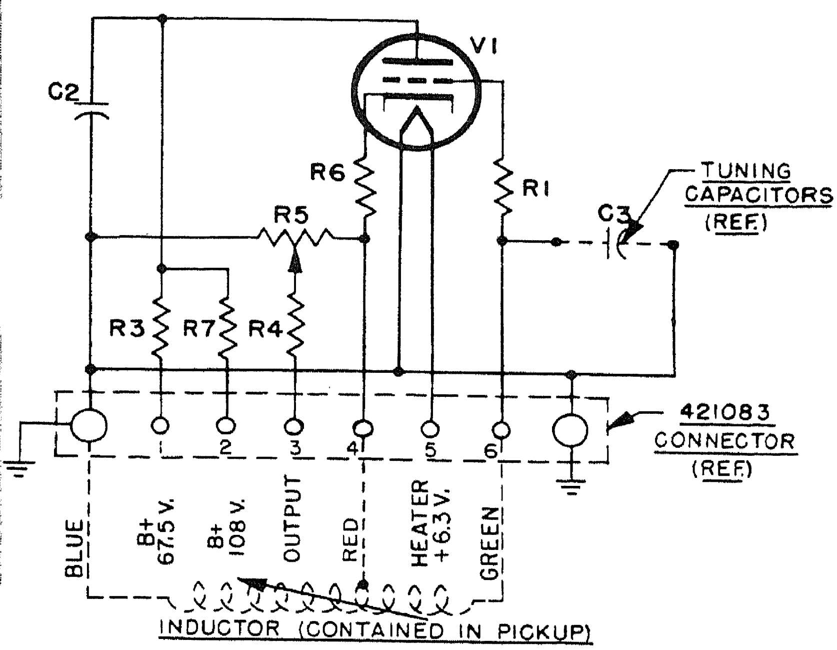
(1) Inductance-capacitance (Fig. 2-14).
(2) Resistance-capacitance phase-shift (Fig. 2-15).
(3) Multivibrator (Fig. 2-16).

The inductance of an L-C tank circuit is often the coil winding of an inductive-type transducer, as already shown in Fig. 2-13. Two typical oscillators are shown in Fig. 2-17. An R-C phase-shift oscillator may use the varying resistance-type transducer as part of the phase-shifting network. Multivibrator oscillators are generally free-running, with their frequency varied by variations in their bias caused by the output of a resistive-type transducer (Fig. 2-18).

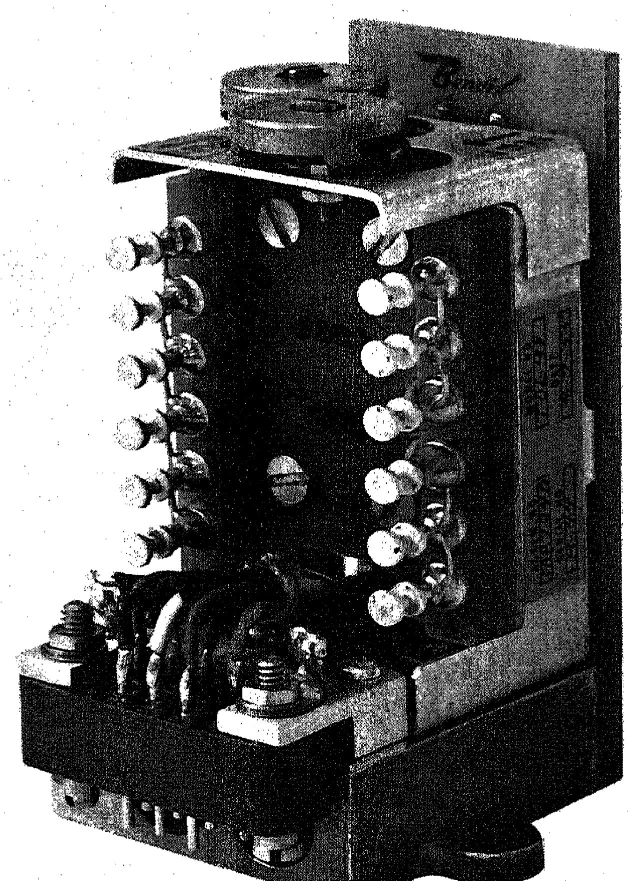
The output frequency of a voltage-controlled subcarrier oscillator may be varied so that an increase in the applied signal either causes an increase or a decrease in the output frequency. The value of input voltage required to achieve ±7.5% frequency swing, or ±15% frequency swing, varies with each manufacturer. An average value is from 3 to 5 volts. The input voltage



INDUCTANCE OSCILLATOR



A



DUAL INDUCTANCE OSCILLATOR

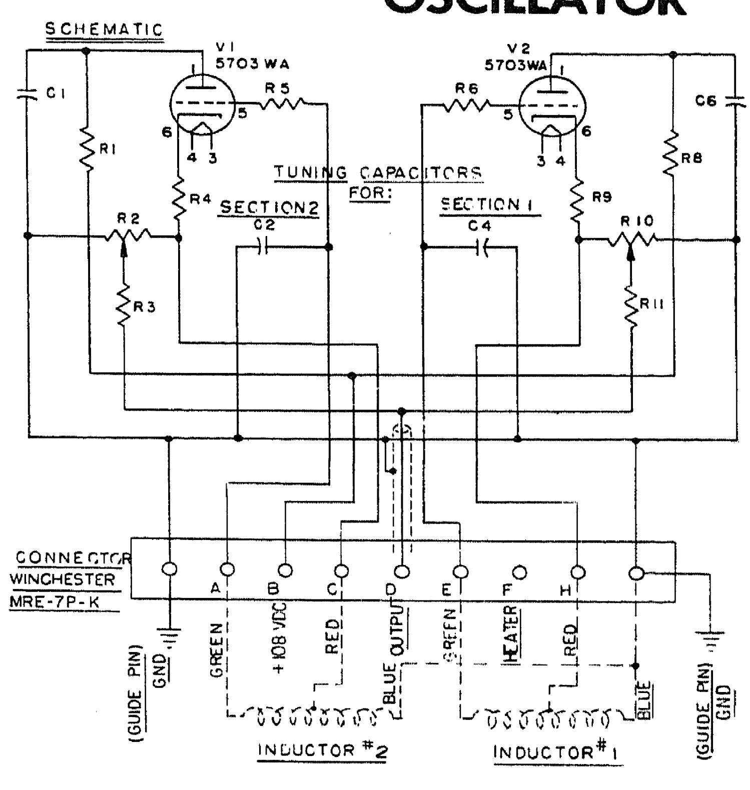


Fig. 2-17

B

VARYING GRID BIAS WITH A RESISTIVE TRANSDUCER

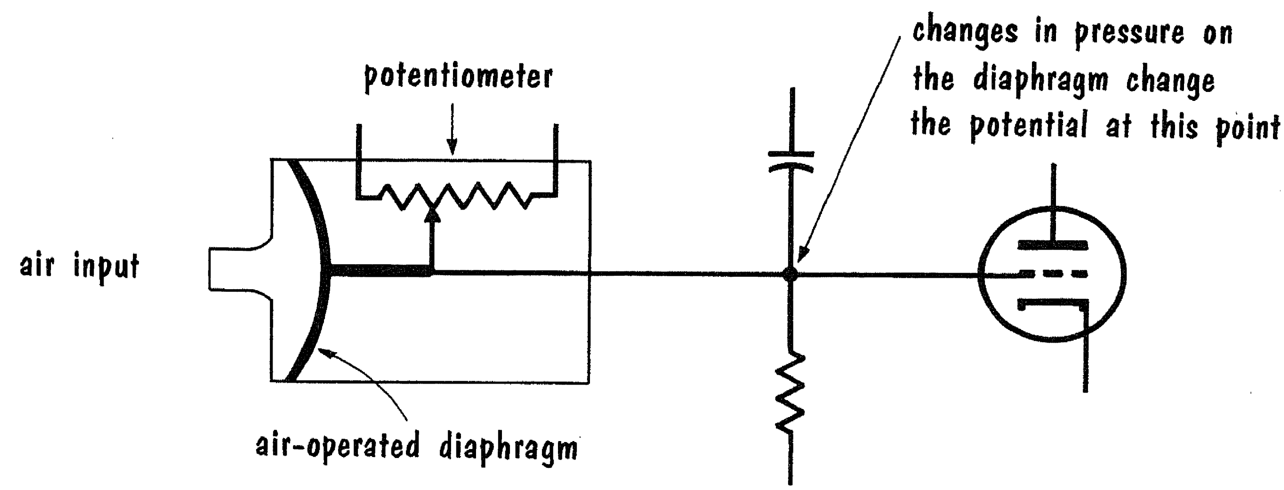


Fig. 2-18

may be unipolar, such as zero to +5 volts, or zero to −5 volts. Or it may be bipolar, such as zero to ±2.5 volts.

In summary, the subcarrier oscillator is a self-contained oscillator that has as its center frequency any one of the 18 IRIG standard values. The subcarrier oscillator is modulated by the varying output of a transducer, most often by FM.

R-f Transmitters

The frequencies used by the higher-channel subcarrier oscillators are still too low in value to be used for efficient r-f transmission. In addition, when two or more subcarrier oscillators are used, only one r-f transmitter is required to transmit the output signals of all subcarrier oscillators.

The output of the subcarrier oscillators is used to modulate the r-f transmitter. The form of modulation used for the r-f transmitter is usually frequency modulation (Fig. 2-19) or phase modulation (Fig. 2-20). Crystal-controlled phase modulation is more prominent. The r-f carrier frequency used is in the 216 to 235 megacycle band assigned for telemetry use.

One problem in having the output of two or more subcarrier oscillators simultaneously modulating the r-f transmitter is cross modulation, or *cross talk*. This results essentially from harmonics of some of the lower-frequency subcarrier oscillators mixing with the primary frequencies of the higher-frequency subcarrier oscillators. Harmonics are generated in nonlinear circuits, or circuits in which overloading causes operation in a nonlinear region. To prevent formation of harmonic frequencies, linear mixing net-

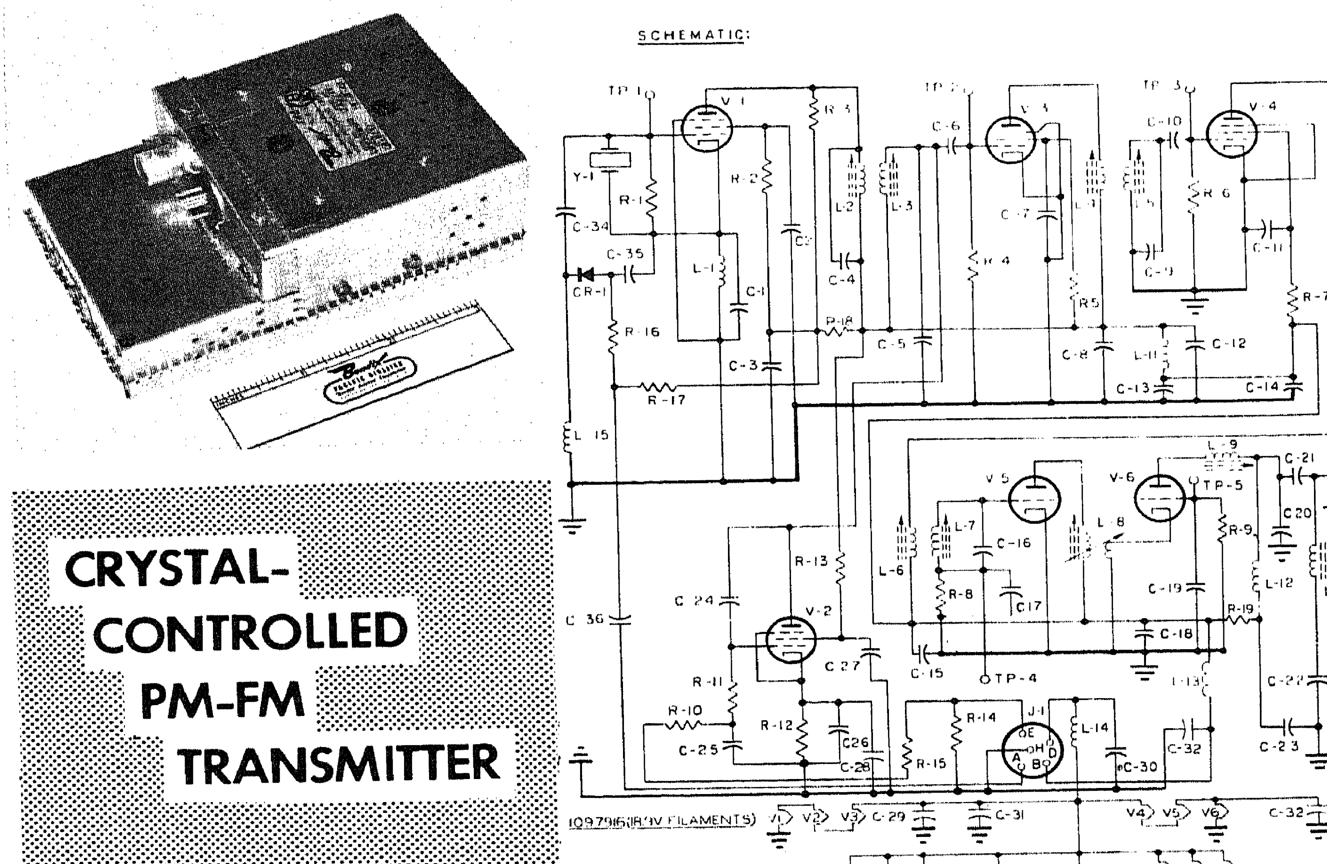


Fig. 2-19

works are used at the output of the subcarrier oscillators. These are sometimes called *harmonic suppression filters.*

To keep an equal signal-to-noise ratio output for all subcarrier oscillators, the higher-frequency subcarrier oscillators must deviate the transmitter more than the lower-frequency subcarrier oscillators. The transmitter fre-

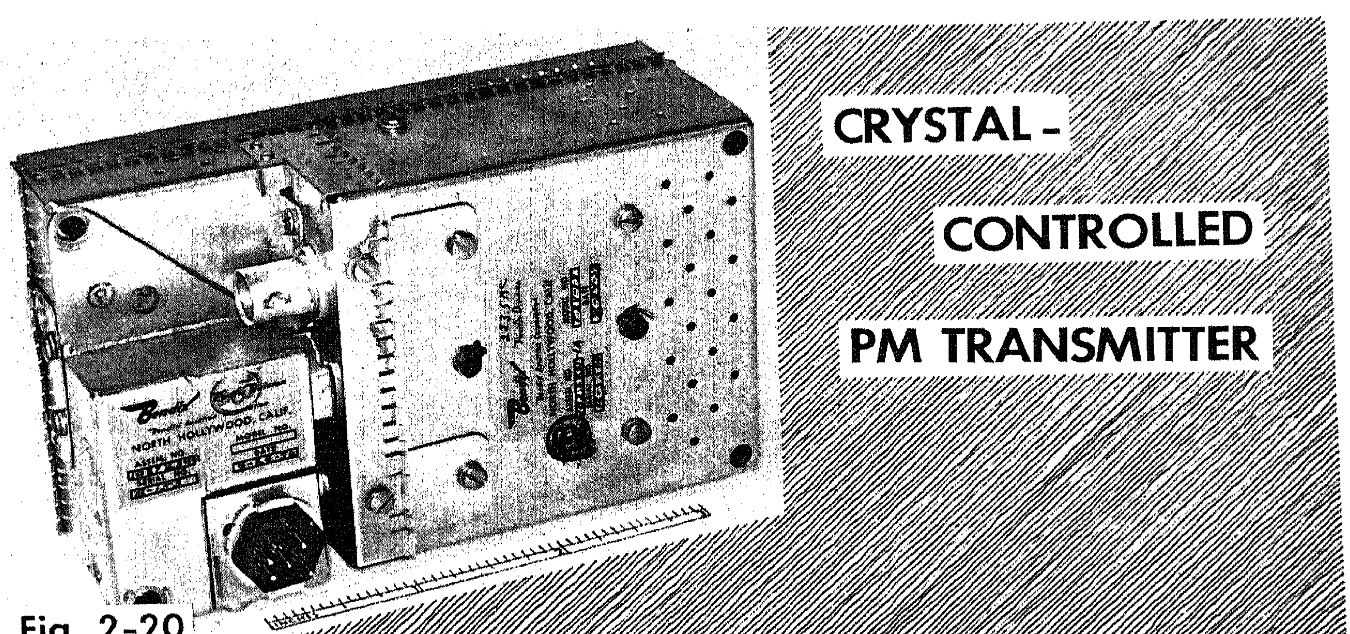


Fig. 2-20

quency deviation of the lower-frequency subcarrier oscillators is kept to a minimum to reduce the effects of cross talk and other problems.

The operating range of the transmitter is to a large degree determined by three factors:

(1) Transmitter power
(2) Receiving and transmitting antenna gain
(3) Receiver sensitivity

The power output of a transmitter averages 3 watts, giving an approximate range of 50 miles under line-of-sight conditions. To obtain higher power, the transmitter is used to drive a high-power r-f amplifier. R-f amplifiers average 40 to 50 watts of output, increasing the range of transmission. The problems encountered in constructing r-f transmitters are the same as those found in constructing all previously discussed telemetering equipment; compactness, ruggedness, and dependability. R-f transmitters pose the additional problem of heat generated in the transmitters. Forced-air cooling has been used for some circuits, others immerse the entire unit in oil for better heat dissipation. Shock is an especially serious threat to the r-f transmitter because a slight movement of some of the tuned-circuit elements causes undesired modulation of the output, producing an erroneous signal. Frequency drift is held to a minimum by the use of high-quality components and other techniques, especially crystal control.

Transmitting Antennas

To transmit r-f power requires an antenna, which must be efficient to make the most of the small power output of the transmitter. An efficient antenna is not difficult to produce under ordinary circumstances. However, on a missile moving at supersonic speed, it is quite a problem. Since the missile may be spinning about its longitudinal axis, as does a rifle bullet, the antenna must radiate in all directions. This may also be accomplished by having more than one antenna. In addition, the sudden acceleration and high temperatures involved require that the antenna be of sturdy construction and correct materials. To keep the missile as streamlined as possible, the antenna cannot be a bulky unit that would alter the missile's shape.

These problems often result in a compromise in the type of antenna used. The most popular types are:

(1) The airframe is the radiator.
(2) Carefully located stubs or wires are used as the radiator.
(3) A projecting portion of the vehicle, such as a fin, is electrically isolated by a notch and used as a radiator.
(4) Slot antennas, mounted flush with the skin of the vehicle, are used as a radiator.
(5) A resonant cavity is used to isolate a portion of the vehicle for excitation as a radiator.

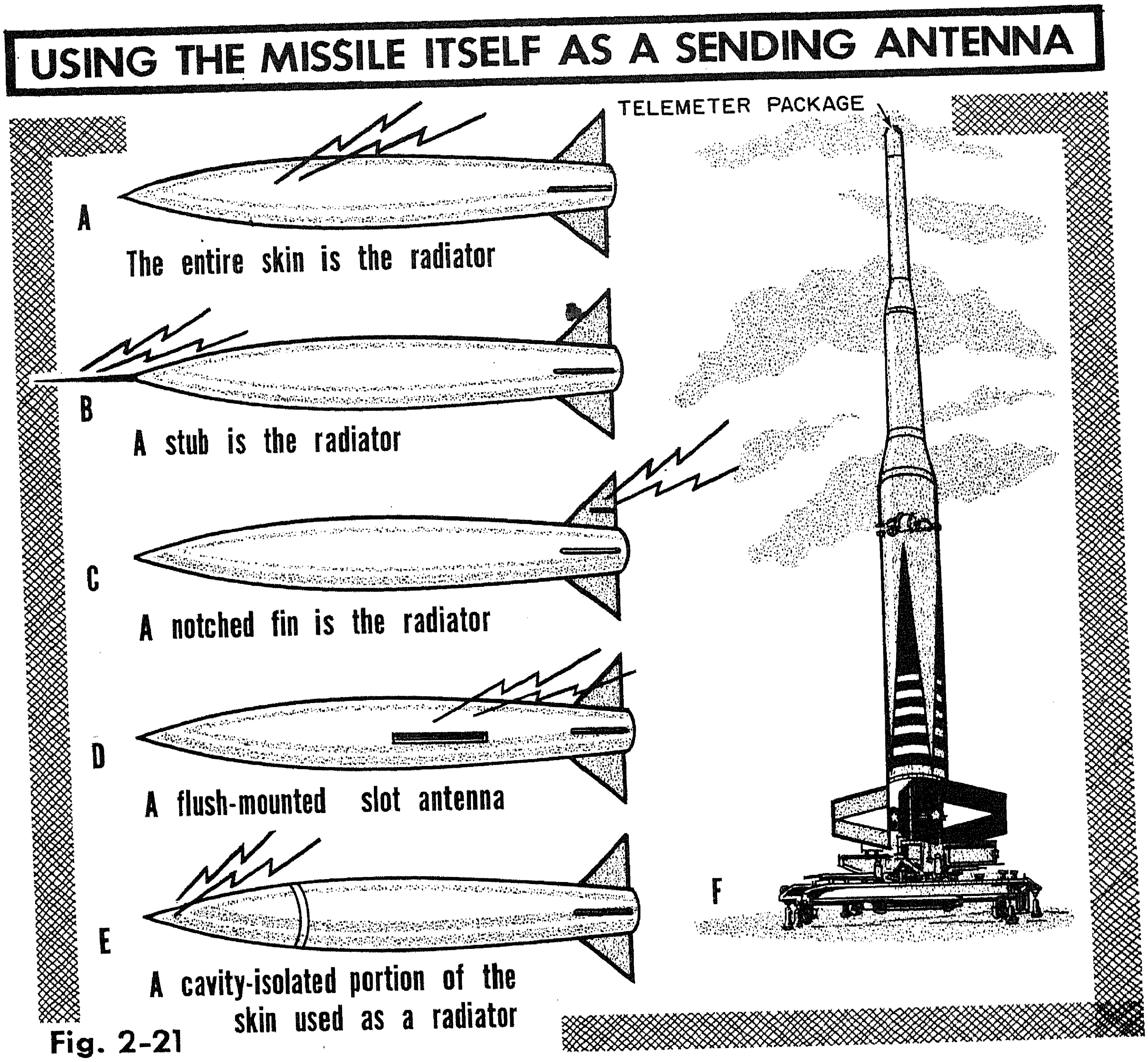


Fig. 2-21

Use of the entire airframe as the radiator is shown in Fig. 2-21A. A *spike* placed in the nose cone of the vehicle is a simple form of stub antenna (Fig. 2-21B). The length of the spike and its use are largely determined by the length of the vehicle. A notch cut through a projecting part of the vehicle, such as a fin, produces a surface suitable for radiation (Fig. 2-21C). (When necessary, the notch is filled with a solid dielectric material.) A slot antenna (Fig. 2-21D) may be mounted flush with the skin of the vehicle. The radiation pattern of this type of antenna is quite similar to that of a dipole and reflector. A fifth method, shown in Fig. 2-21E, utilizes a resonant cavity to isolate the outer skin surface of the forward section, containing the telemeter package, from the rest of the rocket. The outer skin surface of the isolated portion is utilized as a radiator. The cavity creates a high impedance at the selected frequency while maintaining a

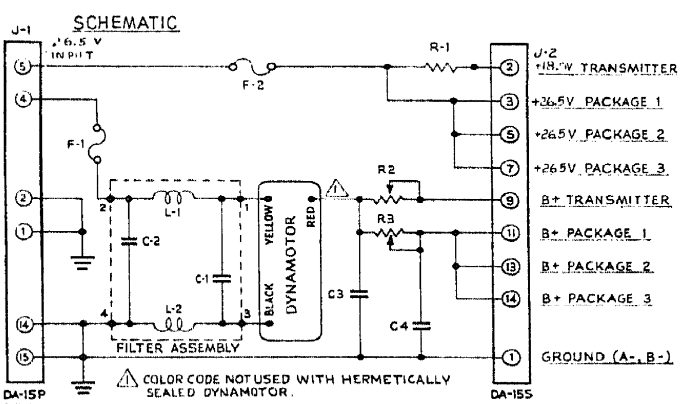
metallic connection between the telemeter compartment and the rest of the missile. The cavity is actually a part of the missile construction and causes no loss of strength or rigidity. This technique is used in the Air Force X-17 missile shown in Fig. 2-21F.

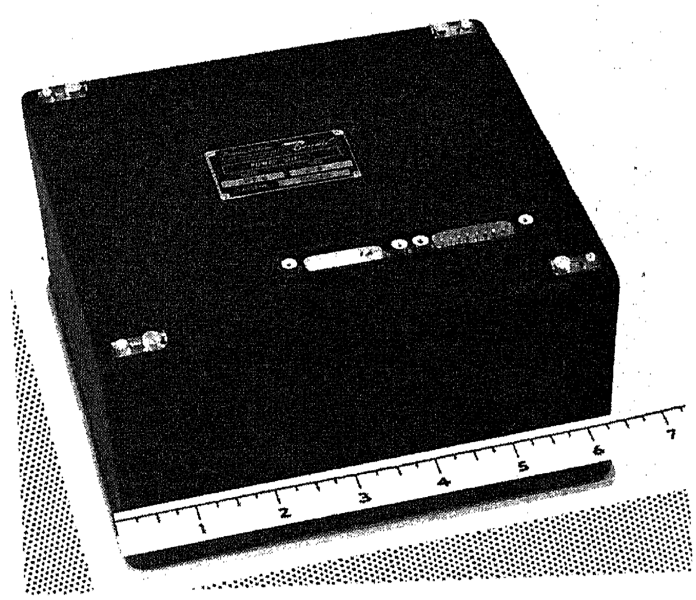
Should the vehicle under test be an aircraft or missile requiring two transmitters, a diplexer may be used. This permits the connection of two transmitters to one antenna, or one transmitter to two antennas.

Power Supplies

Power sources vary from dynamotors and primary and secondary cells to motor generators providing 110 volts at 400 cycles, depending upon the vehicle and the telemetering requirements. In using secondary cells with a liquid electrolyte, special precautions have to be taken to prevent leakage, regardless of the cell position.

Most often the telemetering system has its power supply separate from that of the vehicle. This permits the continued transmission of data even if the power source of the aircraft or missile fails. Since dynamotors are capable of producing high voltages with a low-voltage input, they are often used with batteries providing dynamotor excitation (Fig. 2-22). For short-term





TELEMETER POWER SUPPLY
Fig. 2-22

expendable use, lead-acid cells, of the type used in automobiles but in miniature size, are a typical source. Special-design carbon-zinc cells, similar to flashlight cells, are also used. In some installations the newer mercury cells and nickel cadmium cells are used, depending upon the requirements. Whatever the original source, the voltages as finally applied to the telemetering circuits must be regulated to minimize frequency drift.

3. MULTIPLEXING

Making the Most of Frequency and Time

In the telemetry system of the missile is a transducer that provides a varying output, determined by the medium it is monitoring. That varying output is used to frequency-modulate a low-frequency subcarrier oscillator. The output of the subcarrier oscillator frequency-modulates a high-frequency r-f transmitter, the output of which is radiated by a special-design antenna.

To monitor only one channel, the subcarrier oscillator need not be used in all cases, and the transducer can modulate the transmitter directly. The use of only one channel of information, however, is a rare situation. The usual problem is to monitor many transducer outputs on a limited number of subcarrier channels. The solution is to share frequency, time, or both. Sharing frequency essentially means that one band of frequencies represents one channel of information, another band of frequencies another channel of information, etc. Sharing time essentially means that starting from a prearranged signal, one unit of time represents one channel of information, the next represents another channel of information, etc.

Transmission of more than one channel of information on a single carrier is accomplished by *multiplexing,* involving either *frequency-division* multiplexing (sharing frequencies) or *time-division* multiplexing (sharing time). In one case, each channel is allocated a different frequency band in a given number of frequency bands; in the other, each channel is allocated a different interval of time in a continuously rotating number of channel inputs. Both multiplex systems may be combined to form many hybrid systems.

Frequency-Division Multiplexing

It is possible to use all 18 subcarrier-oscillator channels to monitor 18 variables. The greater the number of channels in use, however, the stricter the requirements of both the transmitting and the receiving station equipment. With all 18 channels in use it is difficult to keep crosstalk out of all channels. As mentioned previously, crosstalk results from harmonics of the lower-frequency subcarrier oscillators mixing with the primary frequencies of the higher frequency subcarrier oscillators. A multichannel system using multiple transducer outputs to modulate subcarrier oscillators and one transmitter is shown in the block diagram of Fig. 3-1. The output of all subcarrier oscillators containing linear mixing networks (to eliminate crosstalk) are mixed together at the input of the FM transmitter. The output of each subcarrier oscillator, being different in frequency, independently modulates the transmitter. This results in mixing of all the subcarrier-oscillator frequencies to produce one complex composite signal. The system of frequency-modulated subcarrier oscillators frequency-modulating a transmitter results in the FM-FM system. (The designations given to this and other systems are listed in the table; it is obvious that a great number of different systems can be formed.)

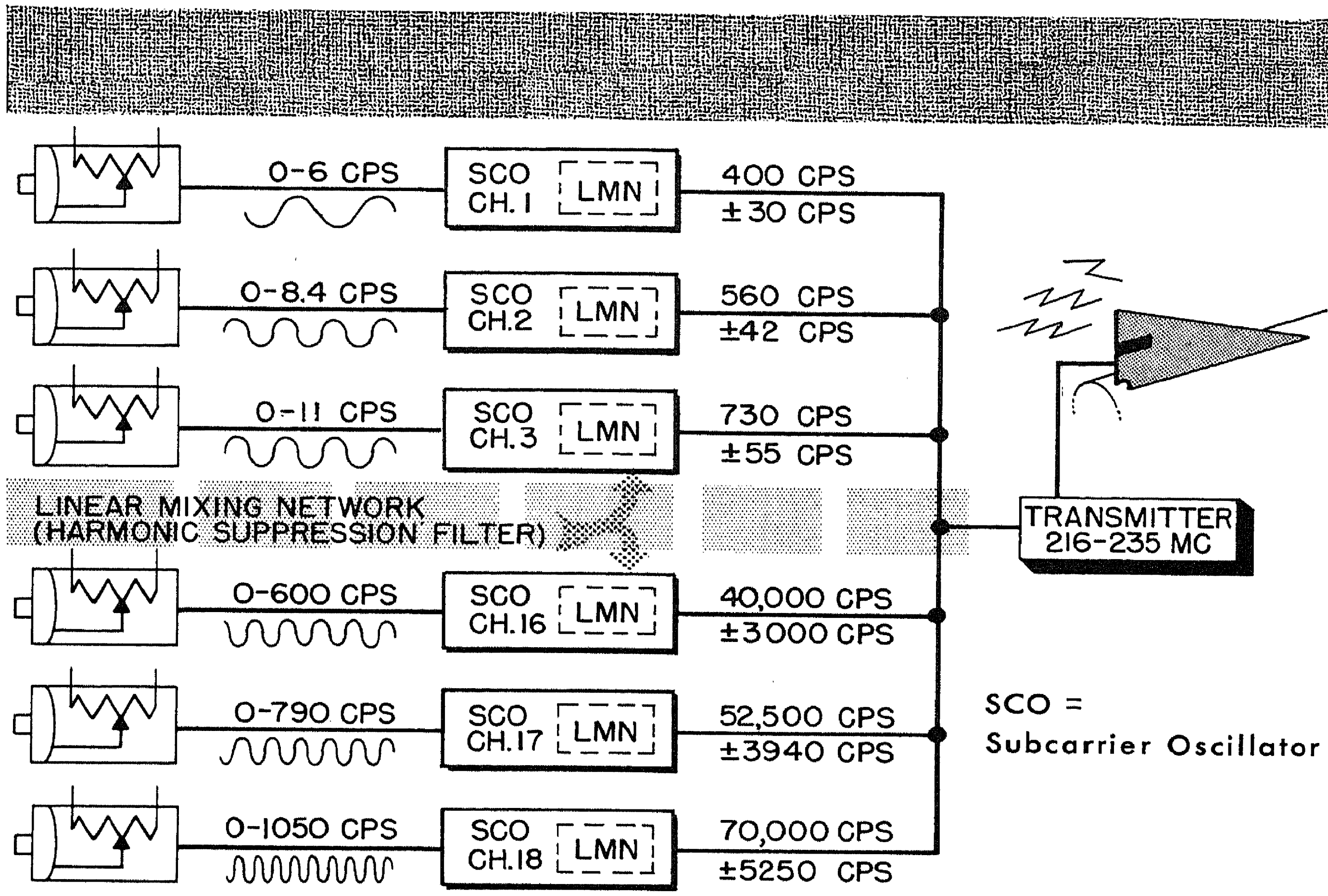


Fig. 3-1 ***FREQUENCY-DIVISION MULTIPLEXING, AN FM-FM SYSTEM***

TELEMETRY-SYSTEM TERMINOLOGY

Name of System	*First 3 Letters Type Of Multiplex (How Signal Is Applied to Subcarrier Oscillator When Used)*	*Middle 2 Letters Type of Subcarrier Modulation (When Subcarrier Oscillator is Used)*	*Last 2 Letters Carrier Modulation*
PAM-FM-FM	Pulse Amplitude Modulation	Frequency Modulation	Frequency Modulation
PAM-FM-PM	" " "	" "	Phase Modulation
PAM-FM-AM	" " "	" "	Amplitude Modulation
PAM-FM	" " "	—	Frequency Modulation
PAM-PM	" " "	—	Phase Modulation
PAM-AM	" " "	—	Amplitude Modulation
PDM-FM-FM	Pulse Duration Modulation	Frequency Modulation	Frequency Modulation
PDM-FM-PM	" " "	" "	Phase Modulation
PDM-FM-AM	" " "	" "	Amplitude Modulation
PDM-FM	" " "	—	Frequency Modulation
PDM-PM	" " "	—	Phase Modulation
PDM-AM	" " "	—	Amplitude Modulation

Frequency-division multiplexing systems other than FM-FM have been devised, a typical example being an FM-AM system. In the FM-AM system, the subcarrier oscillators are frequency-modulated. The transmitter accepts this frequency-modulated input and converts it to an amplitude-modulated output carrier.

Time-Division Multiplexing

A drawback to frequency-division multiplexing is the limiting factor of one transducer to each subcarrier oscillator. To overcome this, time-division multiplexing utilizes transmission of numerous signals on a single carrier. This is accomplished by sampling the transducer output signals in succession, using a sampling or switching device. As previously mentioned, the sampling or switching device, by starting from a prearranged signal, will have one unit of time represent one channel of information, the next unit of time another channel of information, etc. Time-division multiplexing is usually accomplished either by Pulse Amplitude Modulation (PAM) or Pulse Duration Modulation (PDM). An additional method, explained in a later chapter, is Pulse Code Modulation (PCM).

The sampling and switching device (the *commutator*) is the heart of a time-division multiplexing system. Two types are in use, mechanical motor-driven switches and electronic switches. Electronic-switches are common at receiving stations where size and weight are not as critical as is the requirement of constant trouble-free performance. In an airborne vehicle, size and weight are prime considerations, and motor-driven switch assemblies are common. Although the life of a motor-driven switch is shorter than that of an electronic switch, it is ample for the duration of the vehicle flight.

The basic construction of one type of commutation switch is shown in Fig. 3-2. A motor-driven brush holder revolves so that the brush "makes and breaks" with many contacts mounted on a stationary plate. It is important that the motors used be capable of maintaining constant speed, be small in size, and be capable of withstanding severe acceleration and temperature changes. A d-c motor, though smaller in size than an equivalent a-c motor, responds to minor changes in the voltage source, requiring the use of speed governors. The governors and the brushes of the motor have to be serviced at regular intervals. A-c motors have better speed regulation, particularly if the power-source frequency is closely regulated. Although an a-c motor itself is larger than a d-c motor, omission of speed governors and brushes tends to equalize the actual sizes.

Electronic switch circuits vary widely in design. Since vacuum-tube or crystal diodes are excellent switches, being on-off (go/no-go) devices, they are commonly used in electronic switch circuits. Figure 3-3 shows a block diagram in which a free-running multivibrator has its output applied to special circuits that count the number of output pulses. After

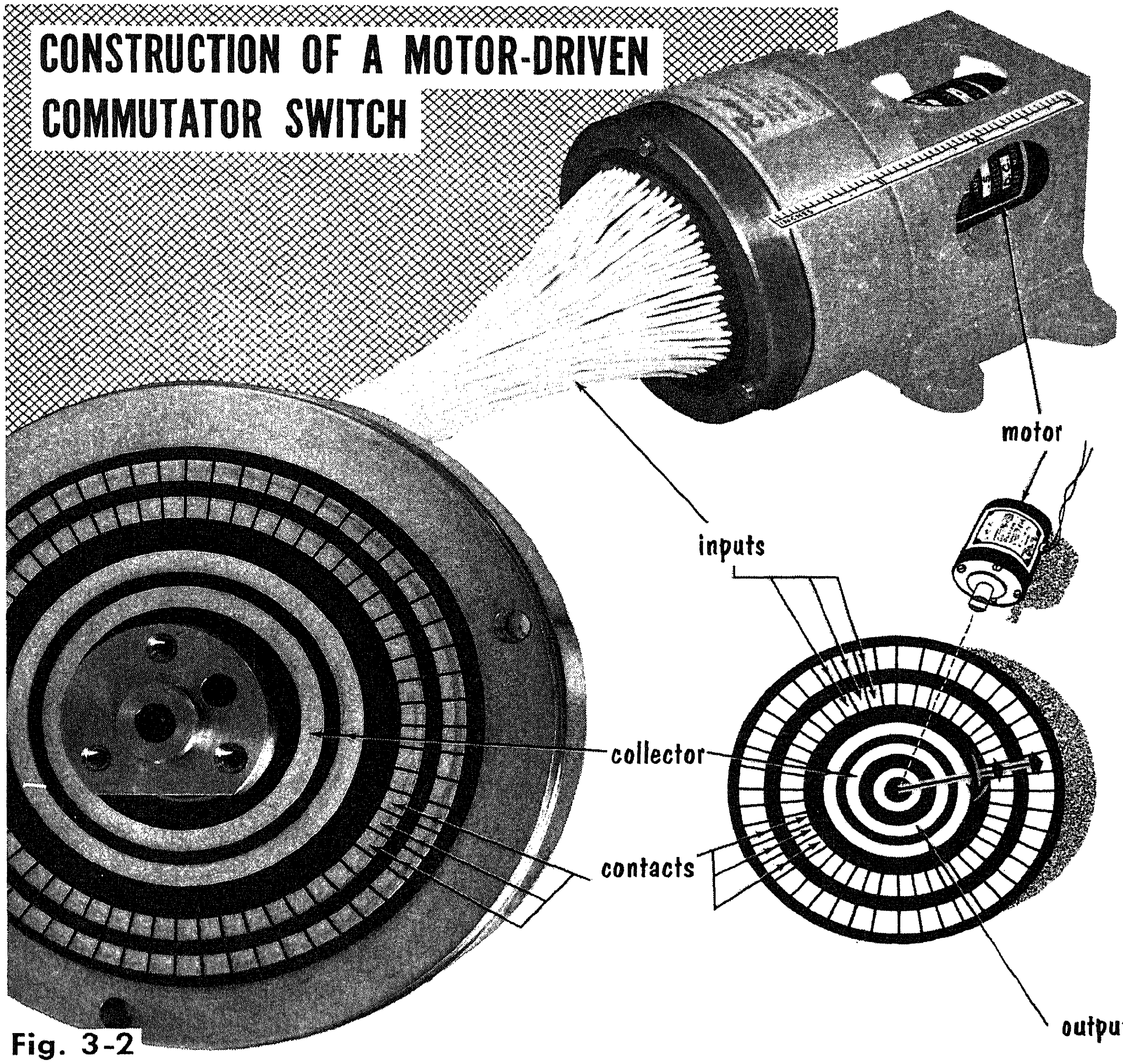

CONSTRUCTION OF A MOTOR-DRIVEN COMMUTATOR SWITCH
motor
inputs
collector
contacts
output

Fig. 3-2

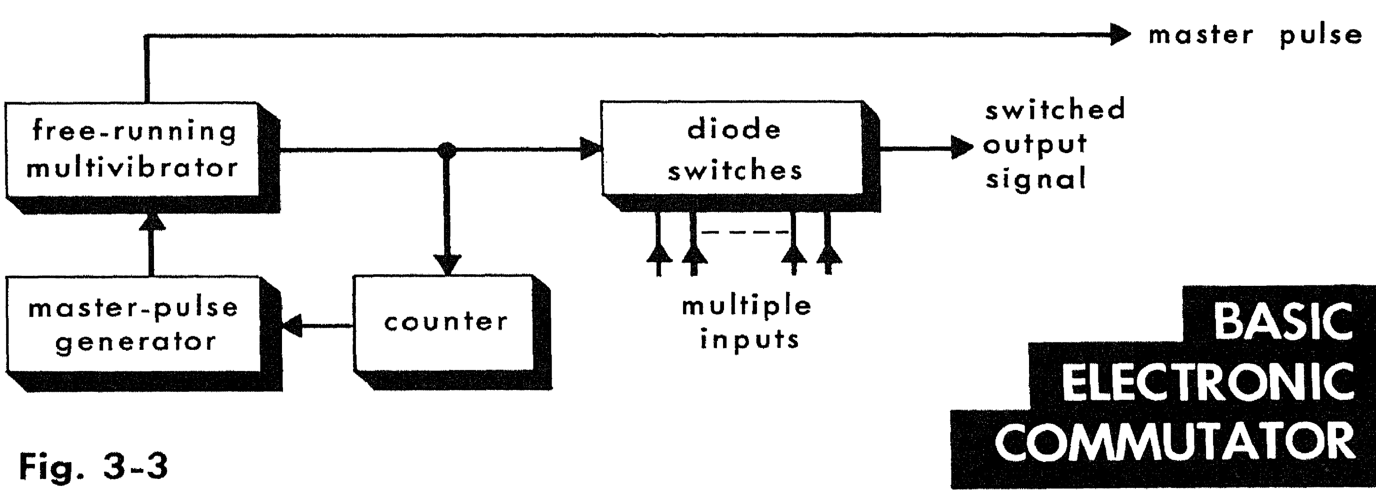

master pulse
free-running multivibrator
diode switches
switched output signal
master-pulse generator
counter
multiple inputs
BASIC ELECTRONIC COMMUTATOR

Fig. 3-3

the proper number of output pulses, a signal is passed to a master-pulse-generator circuit, where the master pulse is developed and applied to control the multivibrator at the correct time. The output pulses of the multivibrator are also applied to a series of diode switches to provide a sequentially switched output of all the input signals.

Pulse-Amplitude Modulation

The output of each transducer is constantly varying, however it is not necessary to follow the output faithfully; constant sampling of the output will provide sufficient information. An example is shown in Fig. 3-4, where

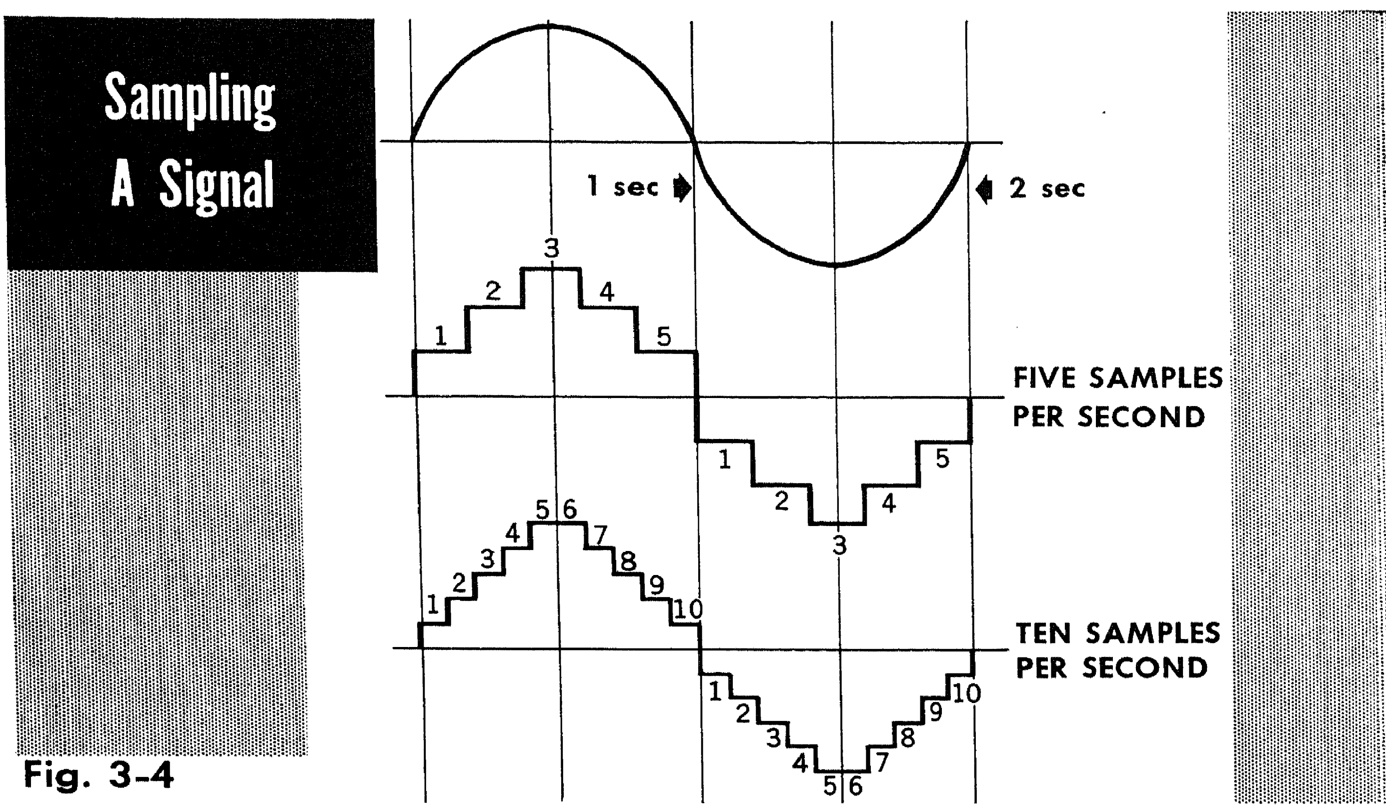


Fig. 3-4

the outline and amplitude of the signal is present in the sampled waveforms. The higher the sampling rate, the closer the sampled signal is to the original signal. Slow variations in the output signal of a transducer need not be sampled as often as fast-changing output signals. Slowly changing outputs can be sampled once per revolution of the sampling switch, rapidly changing outputs may have to be sampled two or more times per revolution. If the sampled transducer outputs are fed to the subcarrier oscillator as a series of pulses of constant width and position, but of varying amplitude, we have Pulse-Amplitude Modulation of the subcarrier. Figure 3-5 shows a basic PAM output from the commutator.

One complete revolution of the commutation switch is called a *frame*. (The number of switch contacts sets the number of samples per frame.) The number of frames completed in one second is called the *frame rate*. The

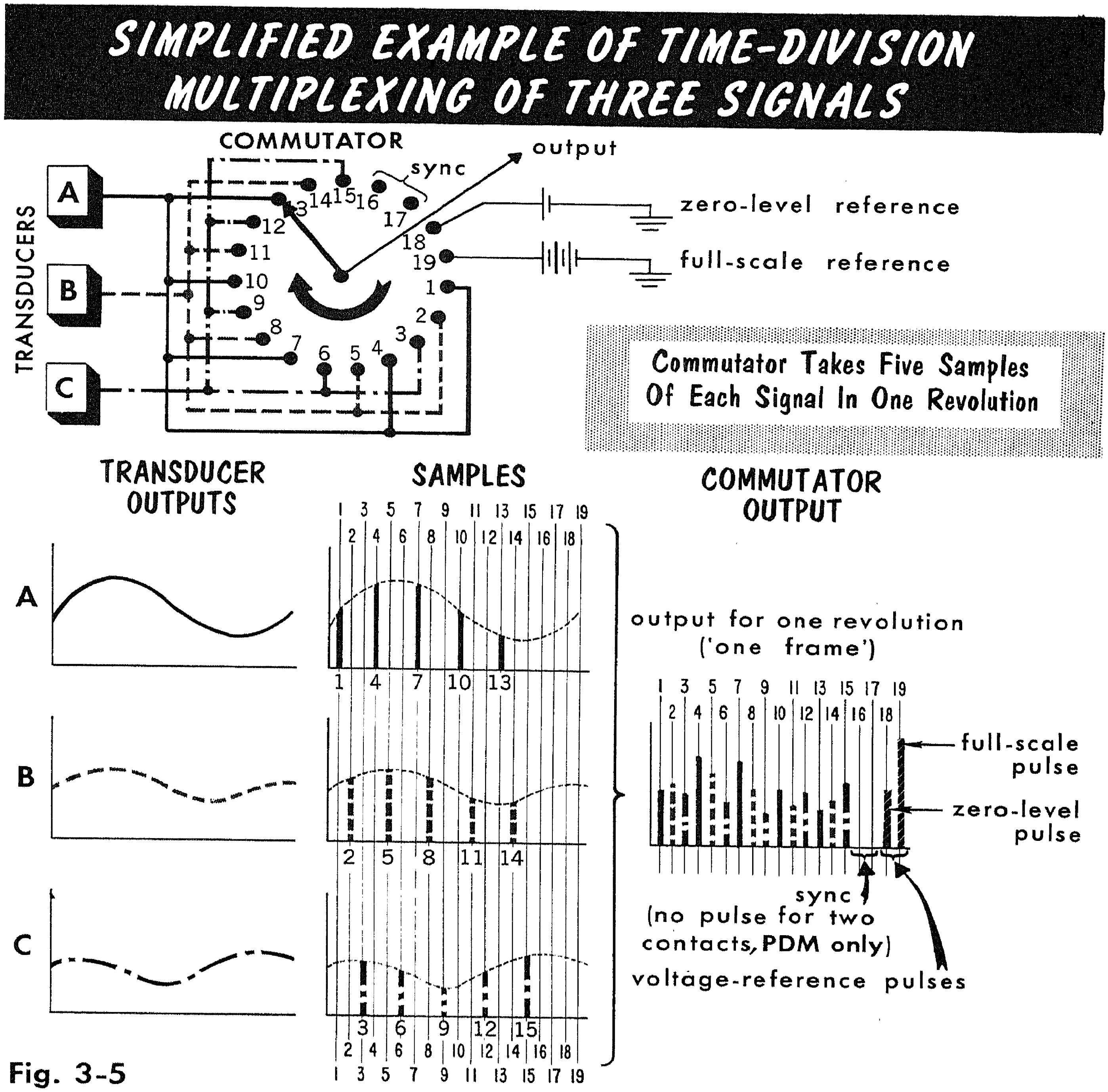


Fig. 3-5

number of samples per frame, multiplied by the frame rate, is the *commutation rate*. The higher the commutation rate, the higher the number of information channels per second, and the higher the subcarrier-oscillator channel required. The higher subcarrier-oscillator channel requirement is due to the increased number of channels per second being transmitted in the same time, requiring increased information being transmitted in the same time. To transmit this increased information in the same time, a wider bandwidth is required and this wider bandwidth is available at the higher subcarrier-oscillator channels.

The various combinations of samples per frame, and frame rates, providing the various commutation rates, are set by the number of transducers to be measured and the frequency of the information being sampled. As previously mentioned, when the frequency of certain desired information cannot be handled by an individual channel, two or more samples of a frame may be used to represent a single function. This, of course, is done at the expense of reducing the total number of information channels.

To insure that the beginning of each frame is accurately known, a synchronizing or master pulse is used. By referencing the various transducer inputs to their position relative to the synchronizing pulse, the reproduction system at the receiving station can locate the output of each specific transducer.

The full title for the system just described is PAM-FM-FM. This denotes that PAM information frequency-modulates a subcarrier oscillator, which, in turn, frequency-modulates a transmitter. When the transmitter is phase-modulated, the name is PAM-FM-PM. A complete PAM-FM-FM system, capable of handling numerous transducer outputs, is shown in Fig. 3-6.

When the number of transducer outputs is sufficiently small to require what would normally be only one subcarrier-oscillator channel in the system described above, it is possible to eliminate the subcarrier oscillator and have the transducers directly modulate the transmitter. The name of this method is PAM-FM, which denotes that PAM information frequency-

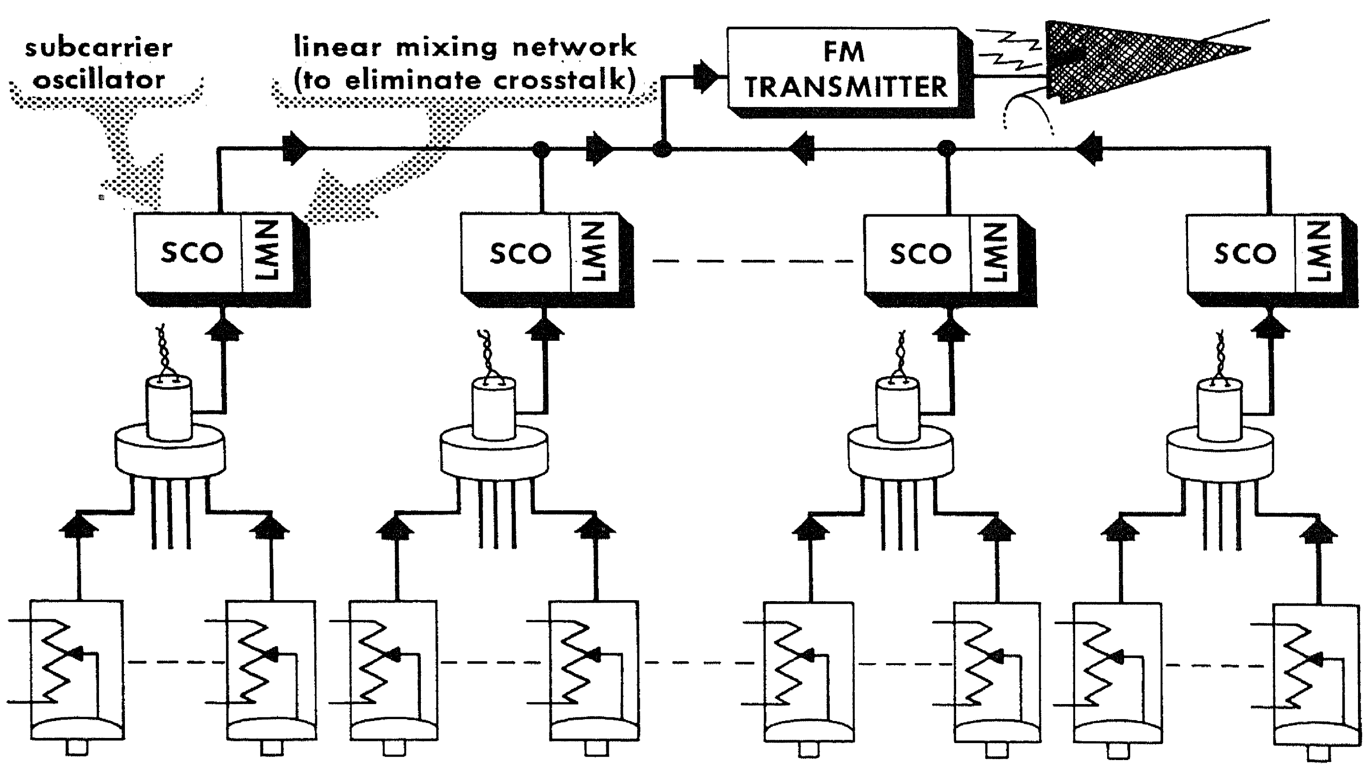


Fig. 3-6 **A PAM-FM-FM SYSTEM**

modulates the transmitter. When a phase-modulated transmitter is used, the method is called PAM-PM.

Pulse-Duration Modulation

The beginnings of PDM are identical with those of PAM. The outputs of the various transducers are applied to the commutation switch. The output of each transducer varies in amplitude, and the output of the commutator is a PAM signal. This is applied to a keyer, or pulse width modulator. The keyer converts the varying-amplitude pulses into constant-amplitude pulses

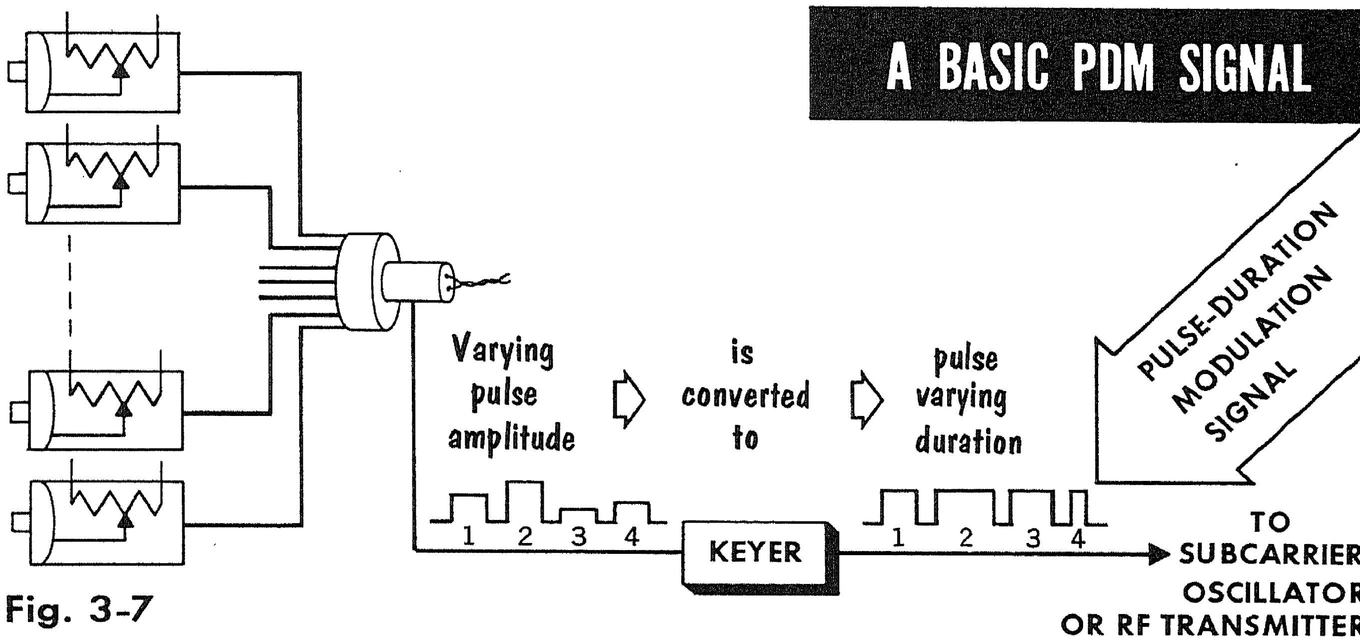


Fig. 3-7

with variable widths. The output pulse of the keyer, as shown in Fig. 3-7, is then applied to a subcarrier oscillator.

As in PAM, one complete revolution of the commutation switch is a frame. The number of switch contacts sets the number of samples per frame. The number of frames completed in one second is the frame rate. The number of samples per frame, multiplied by the frame rate, is the commutation rate. The commutation rate for PDM is always the same; 900 samples per second. The combination of samples per frame and the frame rate that will result in 900 may vary. A typical example is 60 samples per frame with a frame rate of 15 times per second. In PDM, synchronization is obtained by the absence of two successive pulses.

Applying the output of the keyer to frequency-modulate a subcarrier oscillator, which in turn frequency-modulates a transmitter, we have a PDM-FM-FM system. A complete PDM-FM-FM system capable of handling numerous transducer outputs is shown in Fig. 3-8.

When the number of transducer outputs is sufficiently small to require what would normally be only one subcarrier oscillator channel in the

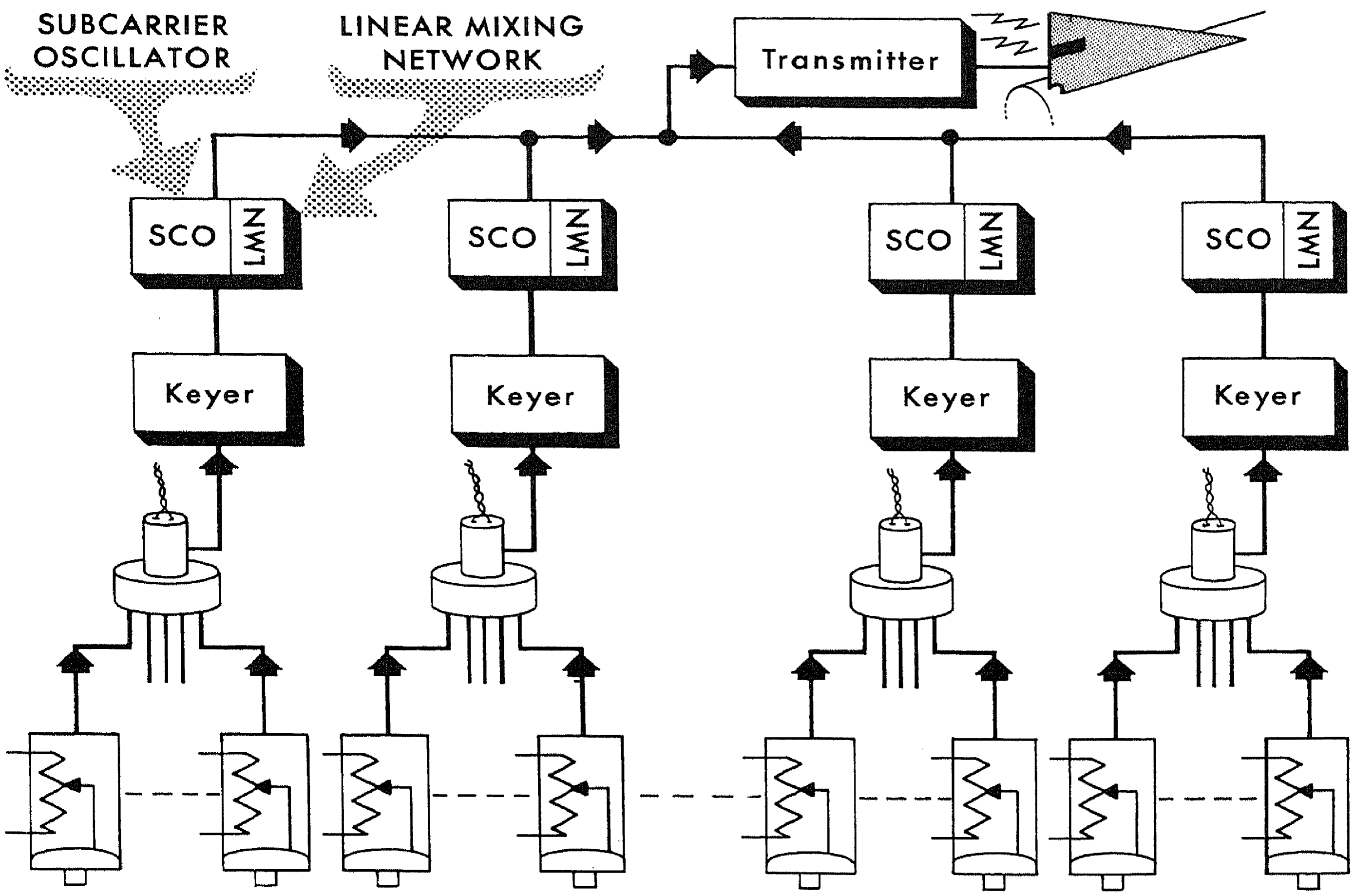


Fig. 3-8 **A PDM-FM-FM SYSTEM**

system described above, it is possible to eliminate the subcarrier oscillator and have the output of the keyer directly modulate the transmitter. The name of this system is PDM-FM.

Advantages and Disadvantages of the Multiplexing Systems

There are advantages and disadvantages in each type of multiplexed signal. The important point, however, is that the enigneers concerned with the many problems, such as available space, weight, power requirements, etc. of the entire telemetry unit must decide what is best suited for their individual needs. Frequency-division multiplexing consists of parallel type circuits; time-division multiplexing of series type circuits. In frequency-division multiplexing the failure of an individual channel will not stop transmissions from the other channels. In time-division multiplexing, a failure in one series-connected unit could very well cause a complete failure of the system.

Frequency-division multiplexing can handle higher-frequency information because of its continuous monitoring of the information channels. Time-division multiplexing requires less bandwidth for the same number of information channels than would be required in frequency-division multi-

plexing. (Several transducers can be used to modulate only one subcarrier in a time-division multiplex system.) A particular advantage of PDM is the fact that it is basically more difficult to distort data measured in time occurrences than data measured in amplitude magnitudes. Occasionally, circumstances warrant a combination of both frequency and time-division multiplexing to form a hybrid system.

4. THE TELEMETRY RECEIVING STATION

Receiving Antennas

The requirements of a receiving antenna are more easily met than are those of a sending antenna. Problems of space, weight, size, etc., are no handicaps at a ground receiving station. The receiving antenna must also make up for some of the restrictions imposed upon the transmitting antenna. It must have high gain to enable it to pickup the low-power transmitted signal. Since the missile spins in flight, the pattern of the receiving antenna must be of circular polarization to prevent any loss of signal when circular polarization is not used in the missile's transmission pattern.

A TYPICAL HELICAL ANTENNA

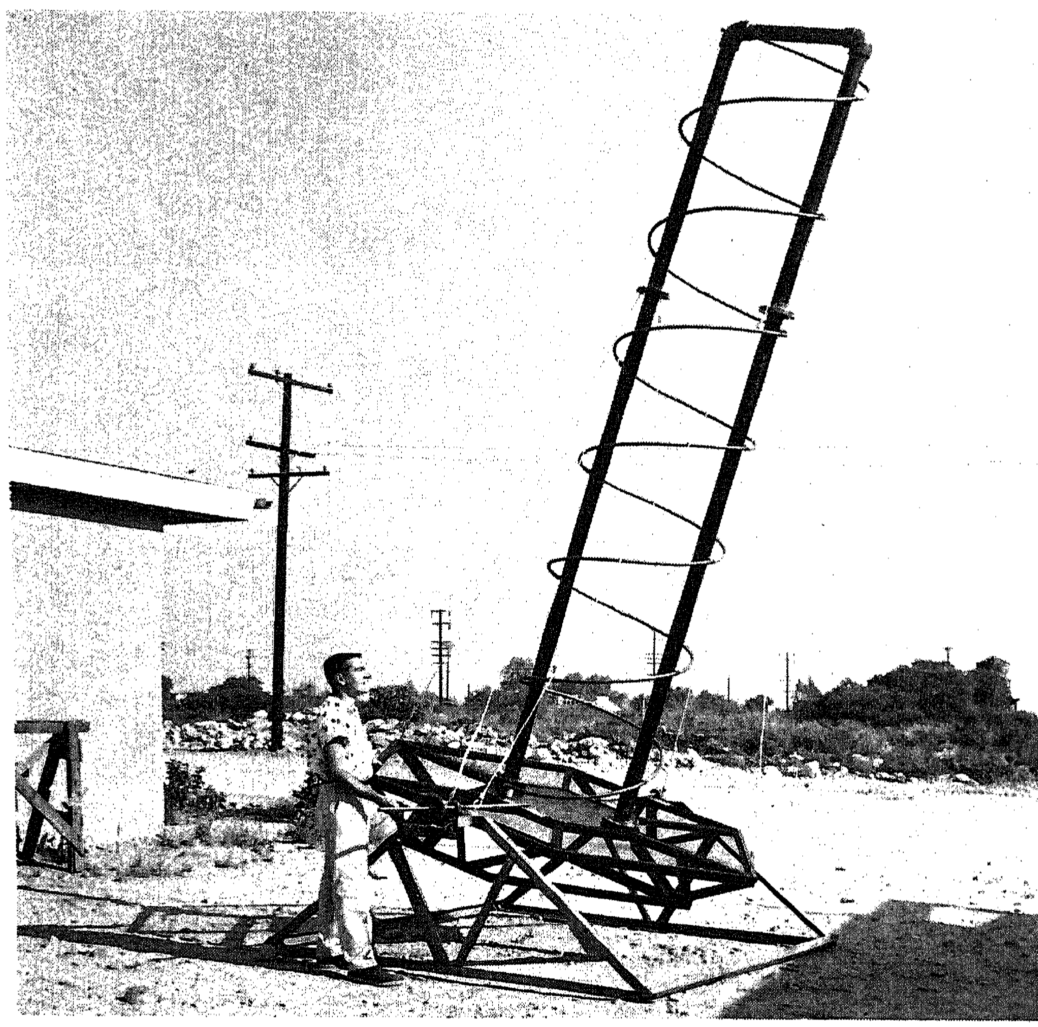


Fig. 4-1

The one antenna shape that satisfies most of these requirements is the *helix,* a form like a screw thread or a spiral (Fig. 4-1). A helical antenna using three and one-half turns, with a ground-plane reflector behind it, provides all the main specifications described above. To increase the gain, more turns may be added (Fig. 4-2). A seven-turn helix narrows and sharpens the beam width, increasing the antenna gain, and results in increased range for the same received signal. The increased range is purchased at the price of increased directivity of the antenna, which in turn increases the difficulty of having the antenna follow the missile flight path.

INCREASING the GAIN and RANGE of an ANTENNA also INCREASES its DIRECTIVITY for the SAME AMOUNT of ENERGY

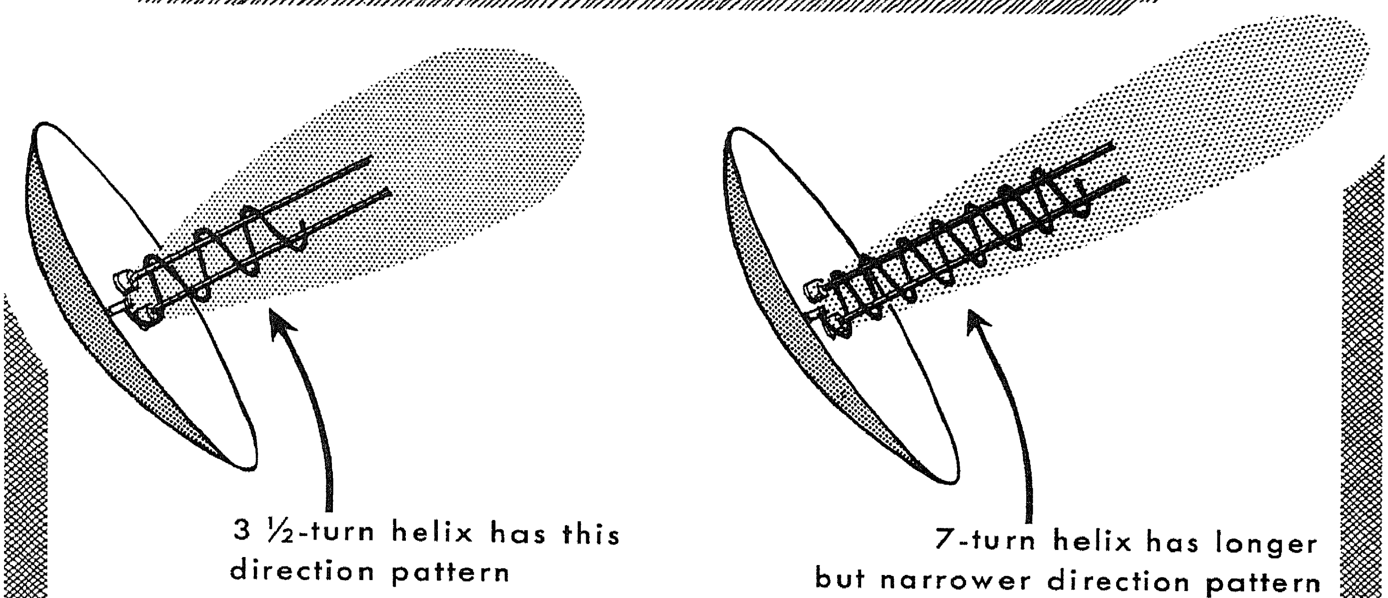


Fig. 4-2

ANTENNA ORIENTATION MAY BE SPECIFIED BY TWO ANGLES

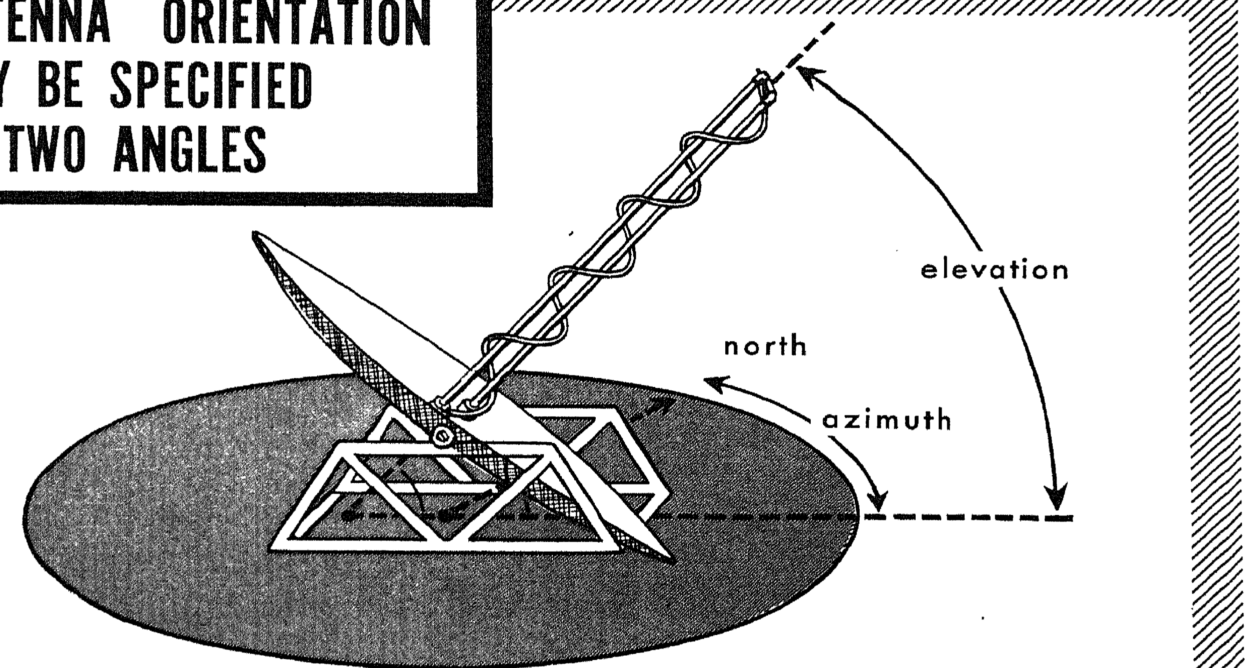


Fig. 4-3

The receiving antenna presents mechanical problems. It must be capable of following the missile in flight, thus it requires special mounting. The antenna mount (pedestal) must permit easy positioning in both vertical and horizontal planes. (The vertical plane is called *elevation,* and the horizontal plane is called the *azimuth,* as shown in Fig. 4-3.)

Radar can be used to track the missile flight path. Special circuits pass the tracking directions to motors controlling the elevation and azimuth of the receiving antenna. The slave receiving antenna thus tracks the missile.

The extremely low power of missile transmitters, the great speed of the missiles, and the increasingly greater distances being covered, have made necessary a special-design telemetry antenna for missile use. The antenna developed is parabola-shaped (like a dish), so it acts as a signal-gathering

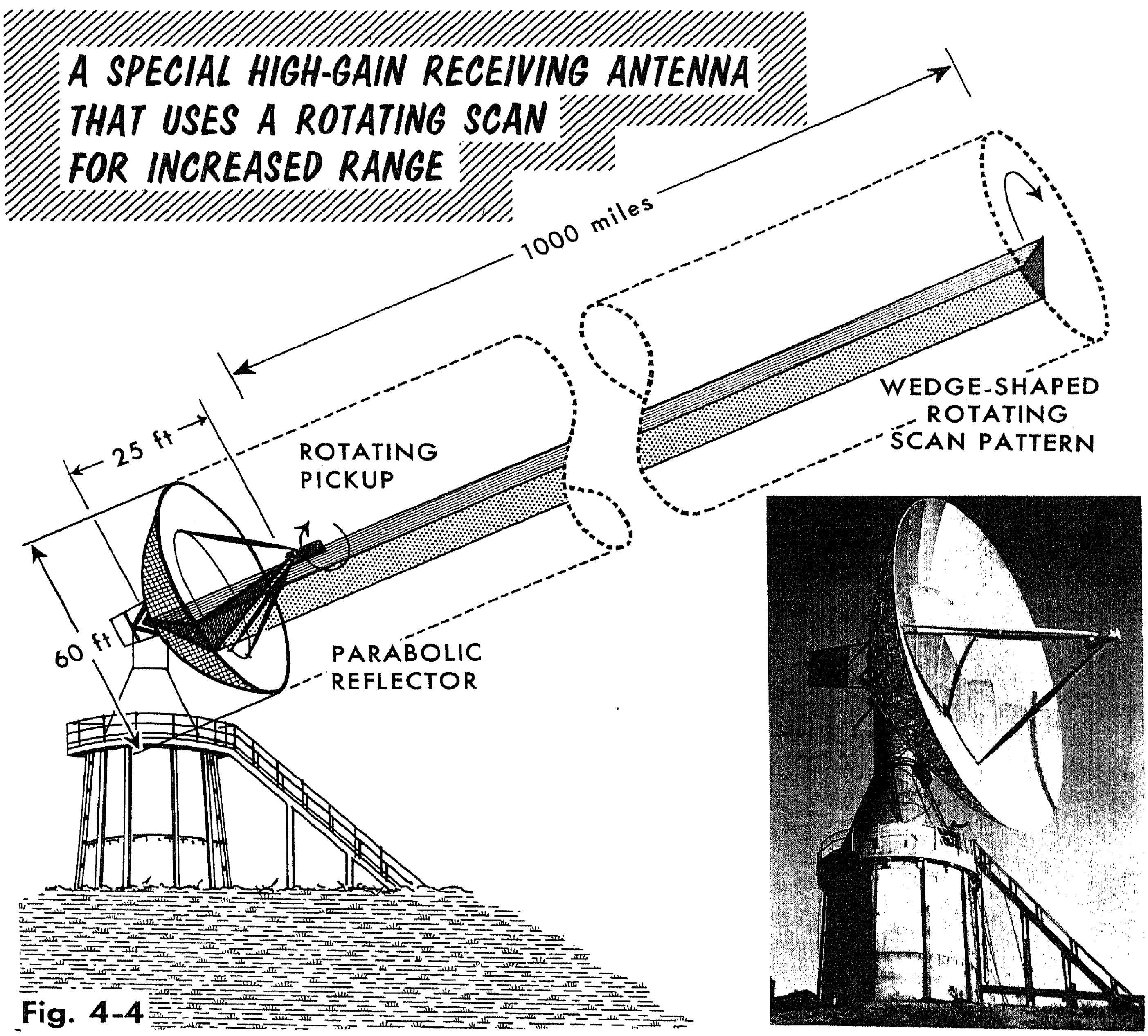
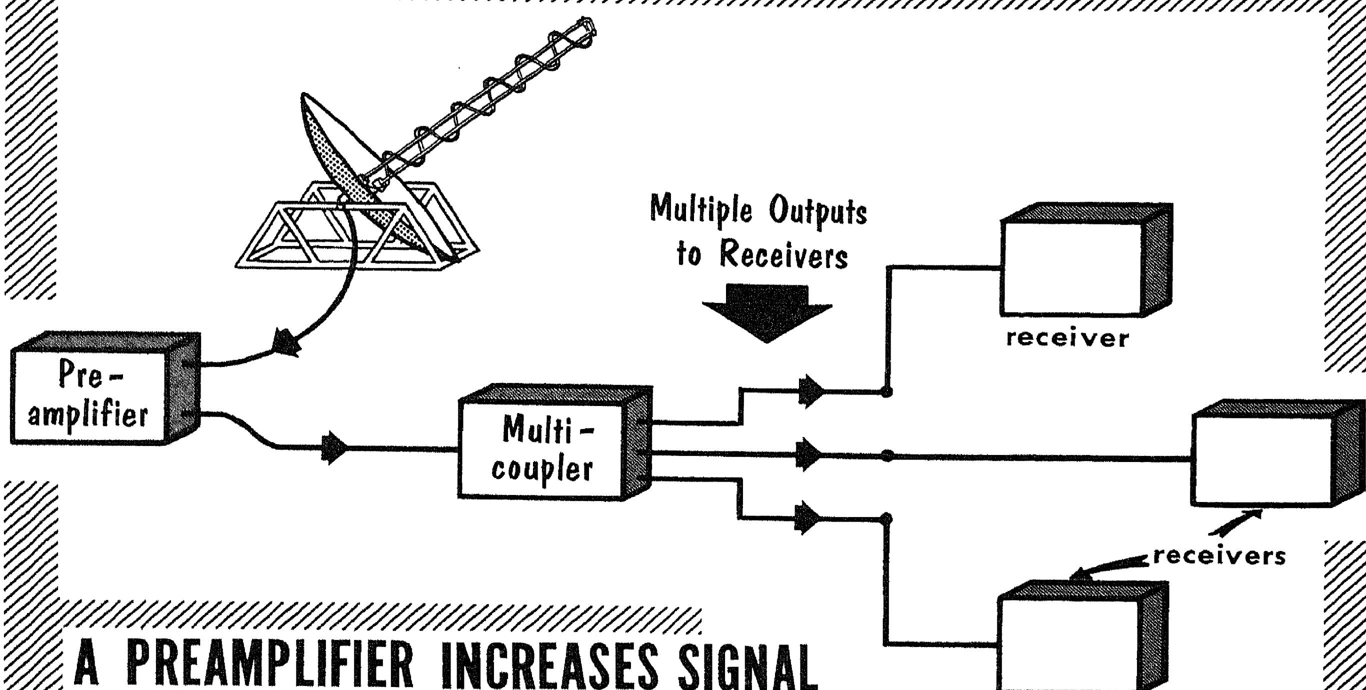


Fig. 4-4

lens with a focal point 25 feet in front of it. A 60-foot diameter dish provides high gain, increasing the distance covered to over 1000 miles with a 30-watt transmitter. Placed at the focal point of the reflector, a special rotating-lens system produces a rotating off-center scan (Fig. 4-4).

The combination of weak signals plus the losses in the antenna-to-receiver coaxial cable necessitates signal-boosting preamplifiers. For best results these are placed as close to the antenna feedpoint as possible—often they



A PREAMPLIFIER INCREASES SIGNAL STRENGTH, AND A MULTICOUPLER PERMITS OUTPUT TO MORE THAN ONE RECEIVER

Fig. 4-5

are mounted right at the antenna. To send signals to several receivers from one antenna, a multicoupler is used. The multicoupler provides multiple-signal outlets while keeping the receivers isolated from each other. The use of a preamplifier and multicoupler is shown in Fig. 4-5.

FM Receivers

The FM receiver must select the desired signal from within the 216 to 235 mc region, amplify it, and demodulate (detect) the r-f carrier. The output is a reproduction of the original composite signal which consists of the mixed subcarrier-oscillator frequencies.

To read the low-level signal input to the receiver, the front end or tuning circuits are designed with special low-noise tubes and circuits to achieve

high gain and a resulting high-level output signal. Since bandwidth and noise level are associated, most receivers have a variable bandwidth selector. This prevents use of any but the required bandwidth, which keeps the noise level at a minimum. Where the entire band must be tuned, the receiver employs vernier (bandspread) tuning to allow accurate reception. Where only one known frequency is to be used, both the transmitter and receiver may be crystal-controlled, providing absolute accuracy and simplifying the problems of drift. Where tuned front ends must be used, Automatic Frequency Control (AFC) circuits are used to keep drift to a minimum.

For increased sensitivity and selectivity, dual conversion is often used. For the second conversion stage, the oscillator frequency is often developed by the use of a crystal-oscillator circuit to maintain stability. The dis-

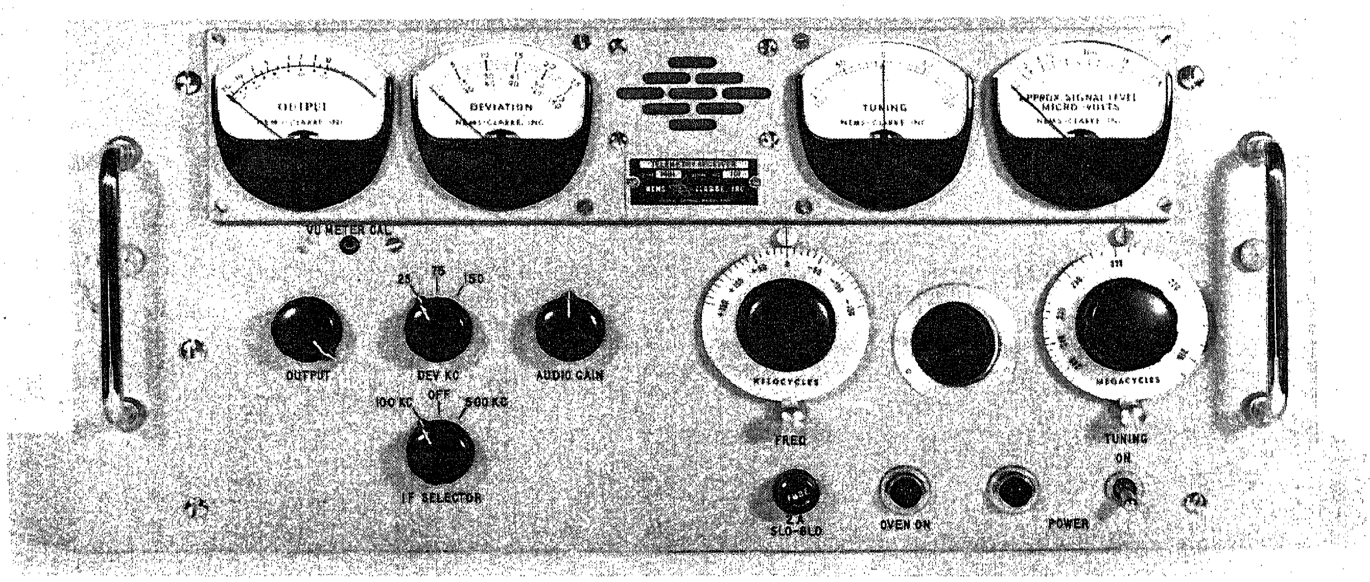


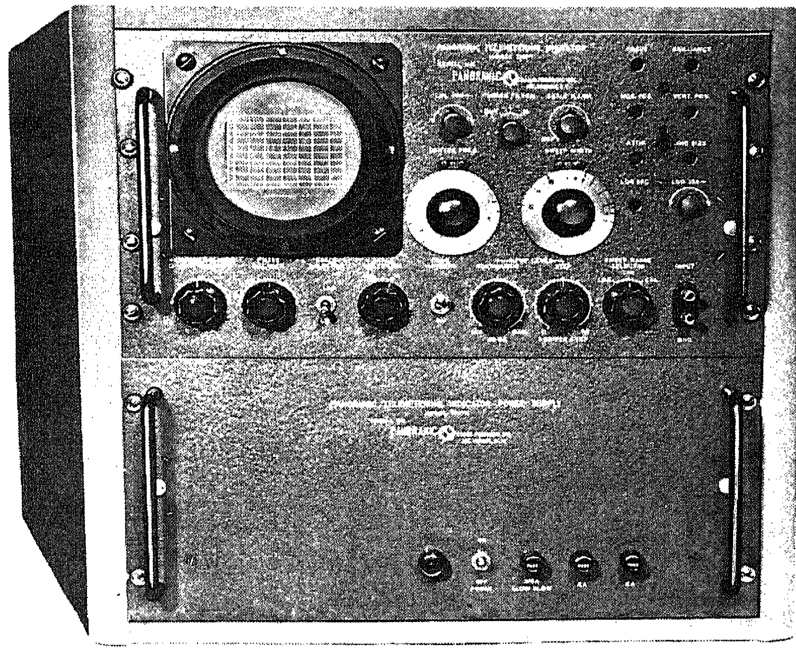
Fig. 4-6 **AN FM TELEMETRY RECEIVER**

criminator circuit must be linear so that all detected subcarrier-oscillator frequencies will receive an output-signal value in exact proportion to the original input-signal level. To aid in monitoring the receiver, meters are used to indicate such variables as input-signal level, output-signal level, frequency deviation, and tuning. A typical FM receiver is shown in Fig. 4-6.

Spectrum Display Unit

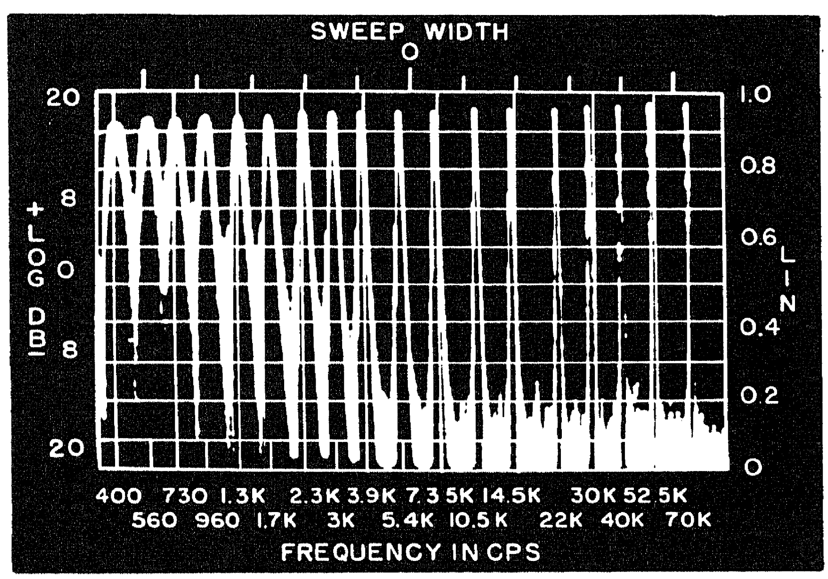
A spectrum-display unit (Fig. 4-7A) is used to monitor the frequency spectrum of the I-F amplifier portion of the FM receiver visually. A visual presentation of the obtained output is shown on the screen of a cathode-ray tube permitting monitoring any or all of the output signals of the subcarrier channels in use. It quickly shows any possible forms of signal interference.

A SPECTRUM DISPLAY UNIT for Visual Monitoring



(A)

A SCREEN PRESENTATION of a SPECTRUM DISPLAY UNIT



(B)

Fig. 4-7 Showing Reception on all 18 Channels

The spectrum-display unit is basically a special-design cathode-ray oscilloscope, engineered specifically to illustrate the signal strength of the output of each subcarrier-oscillator frequency. In addition, by calibration, the spectrum-display unit can monitor the subcarrier-frequency deviations. Figure 4-7B shows a typical screen presentation.

Tape Recorders

Figure 4-8 is the block diagram of a basic receiving station. The incoming r-f signal is picked up by the helical antenna. With preamplification, it is

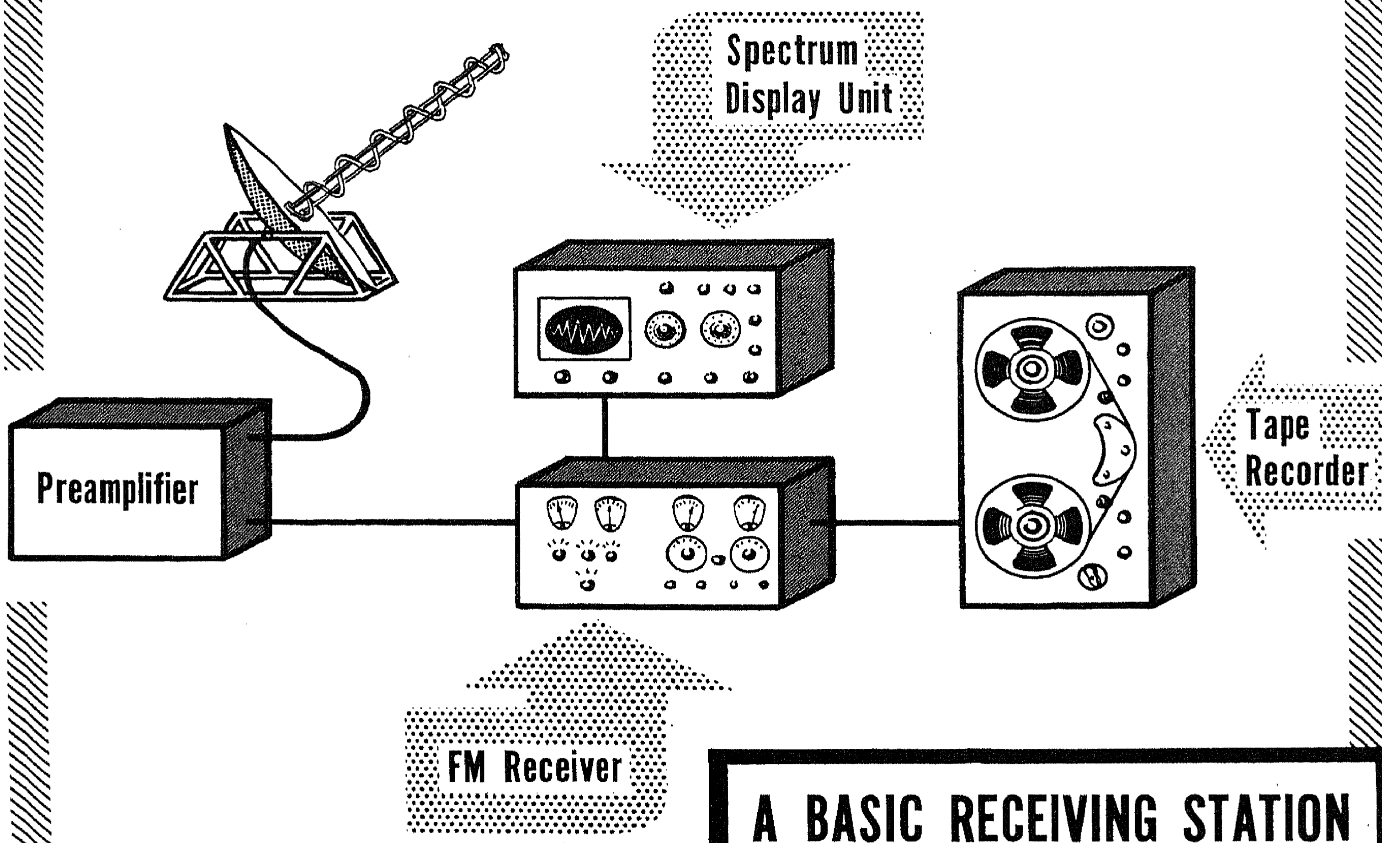


Fig. 4-8 A BASIC RECEIVING STATION

applied to the receiver. The receiver accepts the signal that is being monitored by the spectrum display unit, then demodulates it. The demodulated output of the receiver is a composite signal containing numerous subcarrier frequencies. Since receiving stations are often in inaccessible locations where missiles can be fired without endangering lives or property, the output of the receiver is often placed on magnetic tape and then taken to a special data-handling center. At the data-handling center, the signal is separated into separate information channels. One asset of tape recorders is that one tape can be reproduced on other tapes as a safeguard against loss or accidental erasure. Also, tape recordings permit the information to be run and re-run as often as necessary. The use of tape recorders is so prevalent that a discussion regarding their use, construction, and capabilities is now in order.

The tape itself must withstand extreme temperature and humidity changes. A signal recorded at one location on the tape must be at exactly the same location when it is reproduced. If the tape stretches or contracts, the recorded signal will be changed. Materials in common use for tapes are polyester, acetate and mylar. Tape thicknesses vary; typically they are 1 or 1.5 mil. One advantage of thinner tape is the increased footage it permits on a tape reel. A disadvantage is that thin tape breaks more readily.

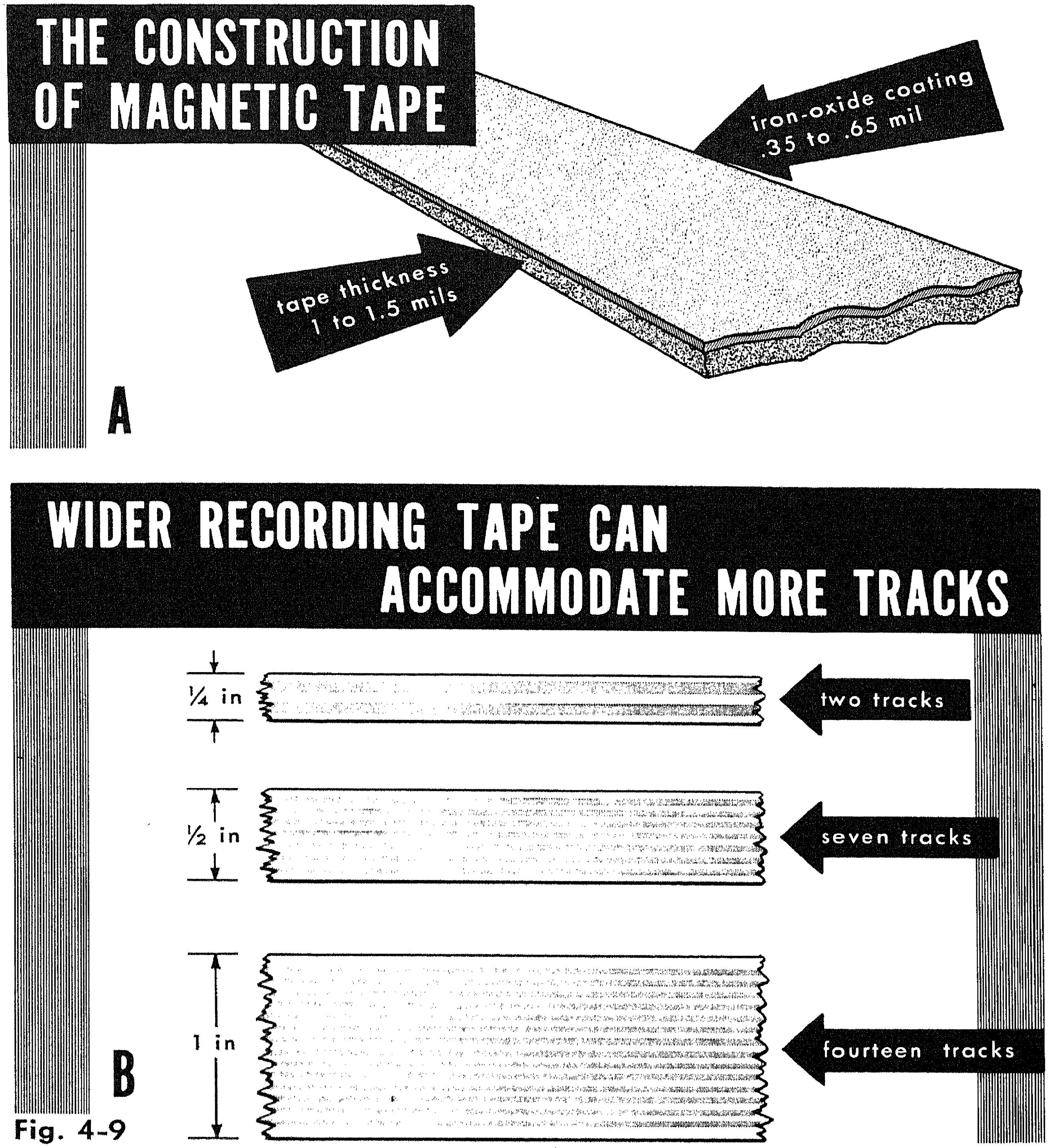


Fig. 4-9

Magnetic iron oxide is coated on the tape in thicknesses from approximately 0.35 to 0.65 mil (Fig. 4-9A). The oxide gives the reddish-brown color to the tape. The dispersal and binding of the oxide is vital—uneven dispersal causes defects in the recording, and loose binding may result in separation of the oxide from the tape, causing a flaw in the recording.

The width of the tape also varies. The standard ¼-inch width used for tape recorders permits recording two signals on two tracks located side by

side. To do this, a special recording head (to be discussed later) is used. Increasing the tape width permits an increased number of tracks to be recorded. As shown in Fig. 4-9B, ½-inch-wide tape can accommodate as many as seven tracks and a 1-inch-wide tape can handle up to 14 tracks.

To magnetize the oxide in the pattern created by the signal, tape-recording heads are used. The recording head, as shown in Fig. 4-10A, consists of an iron core with a small air gap and a coil wound about the core. The signal applied to the coil creates a varying magnetic field. As the tape is drawn past the air gap, the varying magnetic field aligns the oxide coating in a magnetic pattern. For playback, the tape is drawn past a playback head that is similar to the recording head, in the same direction and at the same speed at which it was recorded. As the tape passes the air gap, the varying magnetic field of the tape reproduces the original signal in the coil. To apply signals to more than one track at a time, specially constructed record-playback heads are built with individual heads placed one above the other (Fig. 4-10B).

The frequency response of a tape recorder is directly related to the speed with which the tape is drawn past the record-playback heads. The faster the tape speed, the higher the frequency response, because the increased tape speed permits more tape to pass in a given time. This allows magnetization of the high frequencies without crowding. Different methods are used to vary the tape speeds. Some manufacturers change belts, others vary the motor speed. Some units use a combination of both methods to achieve a complete range of speeds: 1⅞, 3¾, 7½, 15, 30, and 60 inches per second.

To erase the magnetic pattern, the tape is usually passed in front of an erase head. The erase head is similar in construction to a record-playback head. An a-c signal is passed through the erase head to *scatter* the magnetic pattern and demagnetize the tape. In addition to an erase head on a tape recorder, special bulk-erase devices are available for erasing the entire reel at once.

The housing that handles the tape, excluding the amplifiers, is often called the tape deck or the tape-transport mechanism (Fig. 4-11). This consists of three essential assemblies: the tape supply, the tape drive, and the tape take-up assembly. The tape supply is the reel of magnetic tape that is placed on the proper hold-down assembly. The drive consists of a motor-driven capstan. The capstan was originally a nautical device: a windlass to hoist anchors. In tape recorders, it has a similar shape and purpose of driving the tape. The tape is threaded around stationary guides and the capstan, which is speed-controlled by an arrangement of belts, variable motor speed, or a combination of both. The tape is driven by the capstan and is then threaded about the take-up reel.

Various difficulties appear in tape recording, one of which is changing speed. Even minor speed changes may have serious results. The tape-drive

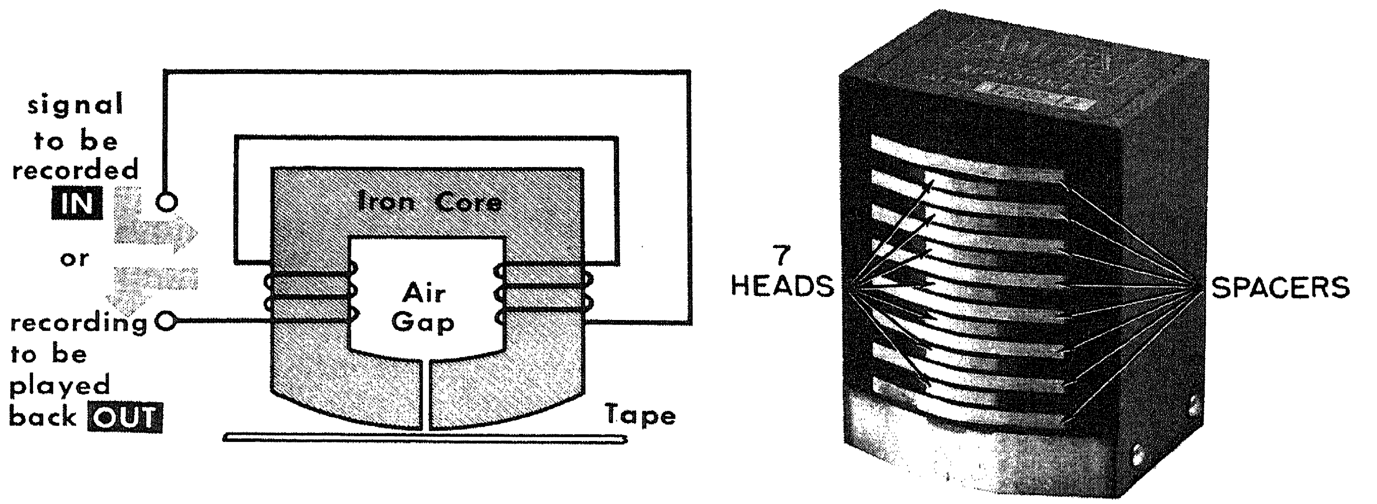


Fig. 4-10 A. Basic Recording and Playback Head for Magnetic Tape B. These Are Stacked for Multitrack Recording

mechanism may not be perfect, resulting in variations in the tape speed called *wow*. (Another source of wow is the tape stretching or contracting due to temperature changes.) An additional problem is the action of the

BASIC TAPE-TRANSPORT MECHANISM

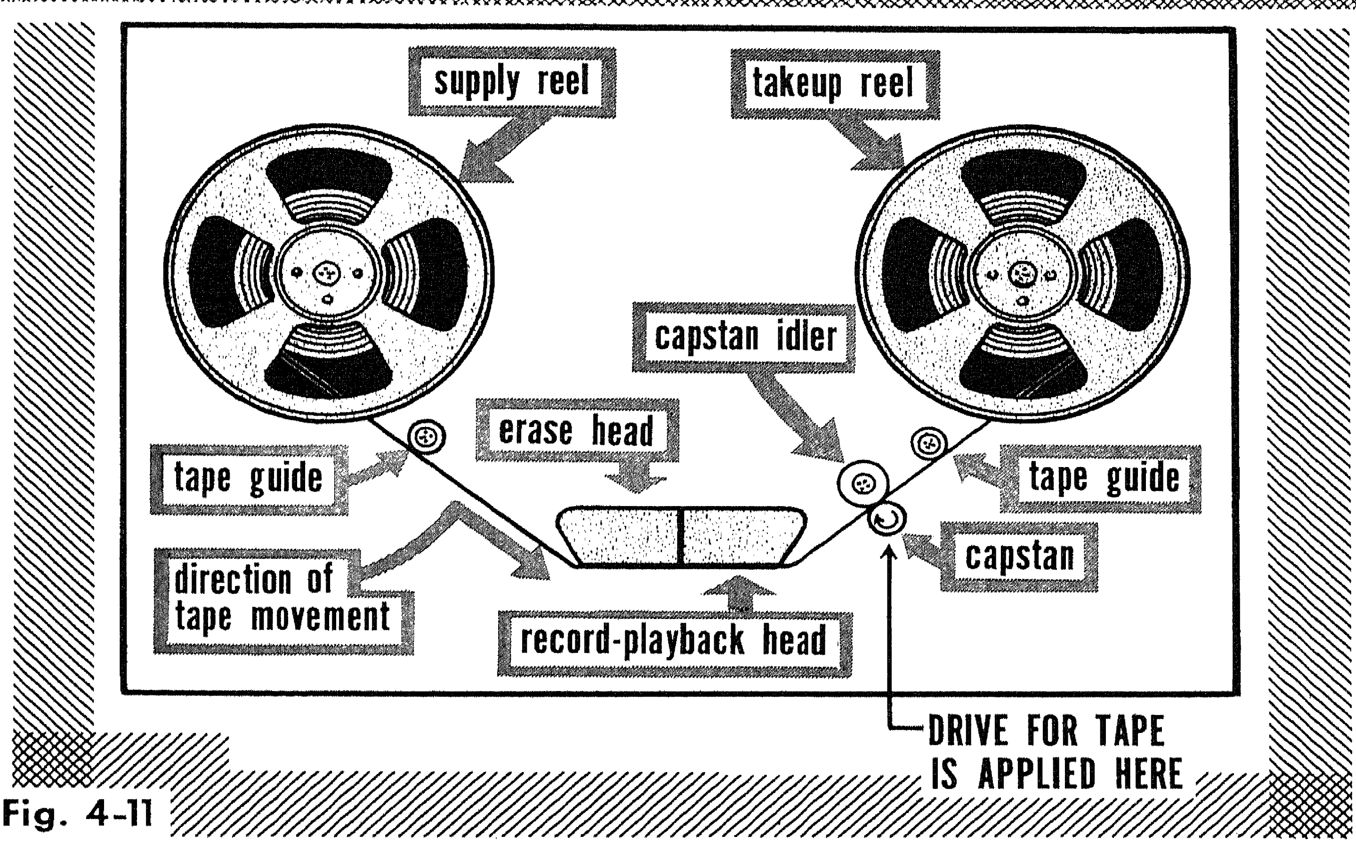


Fig. 4-11

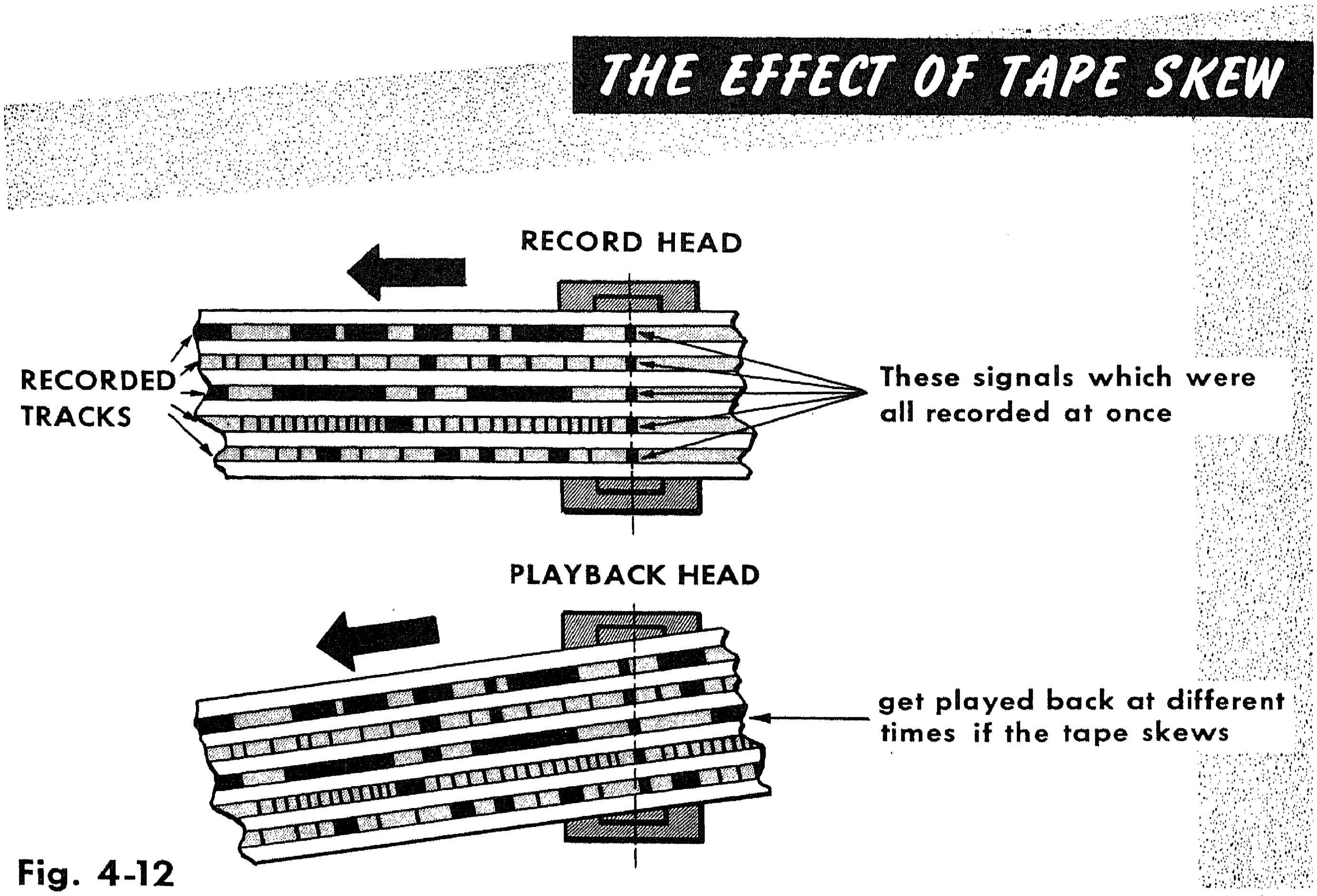


Fig. 4-12

tape as it passes in front of the record-playback head. There is a tendency for the tape to move closer or further away *(flutter)*, which may be caused by varying thickness in the tape and/or its oxide coating. A lesser problem is when the tape does not run in a straight line past the record-playback head, but skews to the side. (This problem is most acute with multiple-track recordings, as shown in Fig. 4-12.)

Time Code

With the increased length of missile flights, single receiving stations no longer have sufficient range to cover an entire flight path. Therefore numerous receiving stations have been constructed along flight paths, with each station covering an overlapping portion (Fig. 4-13). To know the precise time the missile passes through the receiving field of each station, a time code is made common to all stations at once. The use of the time code permits synchronization of all stations and provides an accurate index of elapsed time.

The time code consists of a specific frequency, such as 1000 cycles, which is amplitude-modulated with digital information (to be discussed later), giving the time according to the local time zone or other selected standard. Use of careful design to hold the frequency to very close tolerance permits

using each cycle as a value of time. A breakdown of values in steps of 10 can therefore be made: a single cycle of a 1-kc frequency is 1/1000th of a second, 10 cycles is 1/100th of a second, 100 cycles is 1/10th of a second, and 1000 cycles is 1 second.

Where possible, the time code is sent along a direct transmission line. Where no transmission line can be used, such as on ships, each station

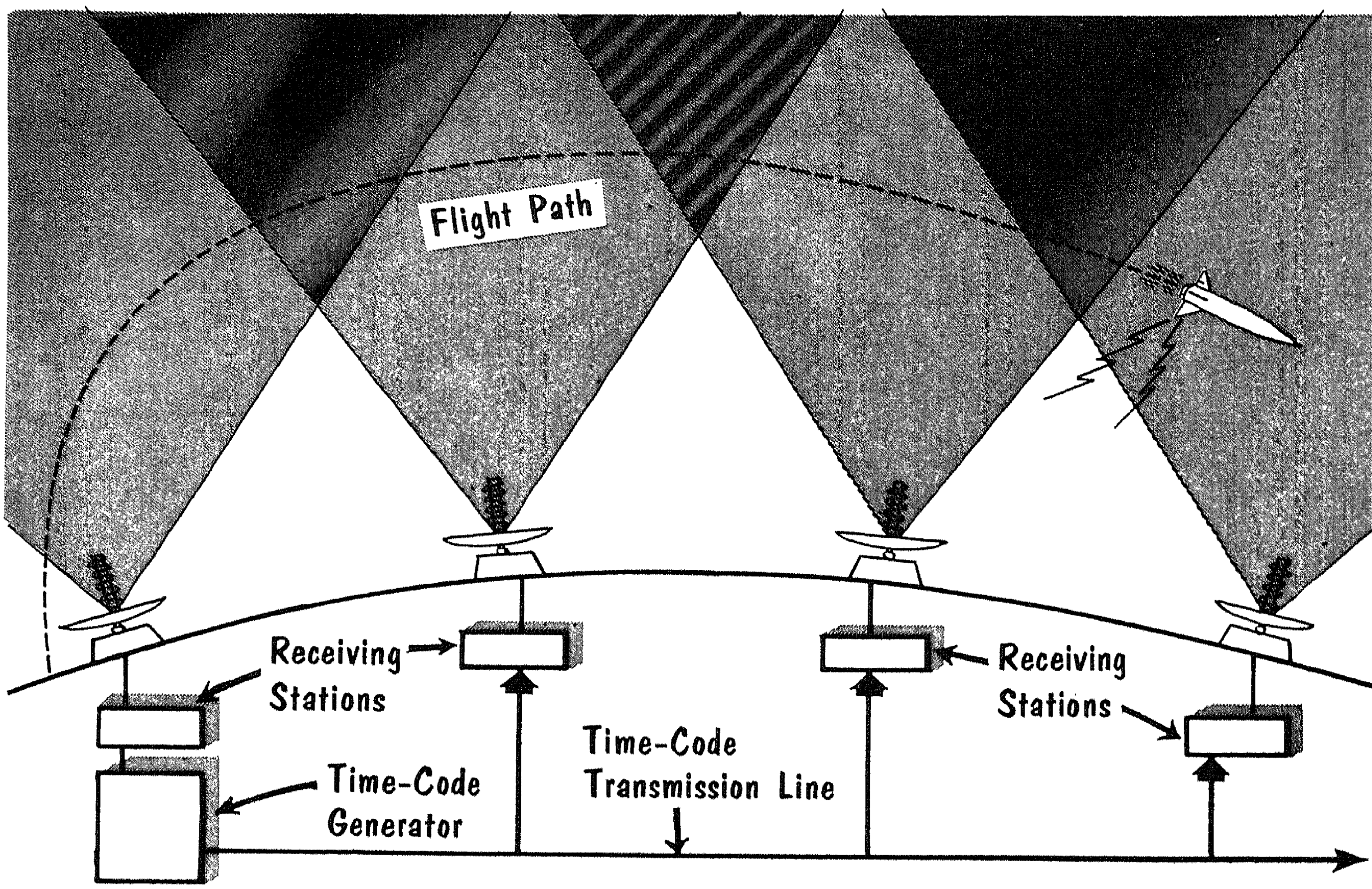


Fig. 4-13 THE USE OF TIME CODE TO SYNCHRONIZE RECEPTION AT A NUMBER OF GROUND STATIONS

generates its own time code. To keep the time code as accurate as possible, the signal is compared with the frequency standards transmitted by the National Bureau of Standards radio stations WWV (near Washington, DC), and WWVH (Maui, Hawaii).

At the receiving station, the time code is placed on a separate track of the recording tape simultaneously with the recording of the signal from the receiver. The time code provides information allowing the editing of the recorded tape of each receiving station. By removing only the portions of tape covering the time in which the missile flew over each station, one tape representing the complete flight may be assembled.

5. RECOVERING AND RECORDING THE DATA

Bandpass Filters

The output of the tape recorder usually consists of one or more output signals, depending upon the number of tracks used. One track contains the composite signal consisting of two or more subcarriers. This is the equivalent of the signal that is applied to the transmitter in the missile.

To separate the individual subcarrier frequencies that comprise the composite signal, special bandpass filters are used. Bandpass filters are tuned circuits that pass only a specific band of frequencies. Careful circuit design and choice of component values permit the use of filters designed to pass only the complete range of frequencies of each individual subcarrier channel. Applying the composite signal to a bank of filters as shown in Fig. 5-1, results in an output for each subcarrier-channel frequency. The output of each bandpass filter will be a duplicate of the output of each original subcarrier oscillator in the missile.

FM Discriminators

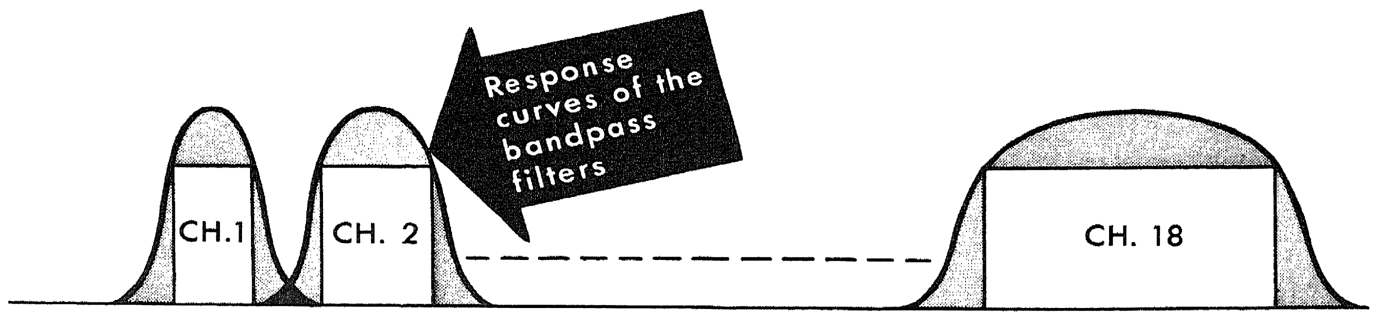
The FM subcarrier variations at the output of the bandpass filter are next applied to an FM discriminator. The FM discriminator is used to convert the variations of subcarrier-oscillator frequency back to the original information signal that was applied from the transducer. The discriminator output must be an exact duplicate of the input to the subcarrier oscillator, which requires linear discriminator response. (Specific changes in frequency must result in exactly proportional changes in voltage output.)

Many FM discriminators (circuits that remove the audio modulation or intelligence from the r-f carrier) have been used in FM radio receivers operating in the broadcast bands. The simplest method is that of slope detection. This was soon replaced by the more reliable Round-Travis discriminator. In turn, a still more reliable circuit for FM detection is the Foster-Seeley discriminator. However, all of these proved inadequate for use in radio telemetry. Special circuitry was needed.

Pulse-Averaging

A typical method of converting changes of frequency into proportional changes of voltage that is used in telemetry involves pulse-averaging circuits. The block diagram in Fig. 5-2 illustrates the basic requirements of a pulse-averaging discriminator. The four main circuits are the axis-crossing detector (which provides a pulse for each axis crossing of the input signal), the delay circuit (which provides a delayed pulse), the current source (which supplies a current determined by the input frequency), and a filter that yields an output voltage determined by the average current from the current source.

As shown in the timing diagram, the input signal, after amplification, is applied to an axis-crossing detector. The circuit develops a pulse each



USING BANDPASS FILTERS TO BREAK THE COMPOSITE SIGNAL INTO INDIVIDUAL SUBCARRIER FREQUENCIES

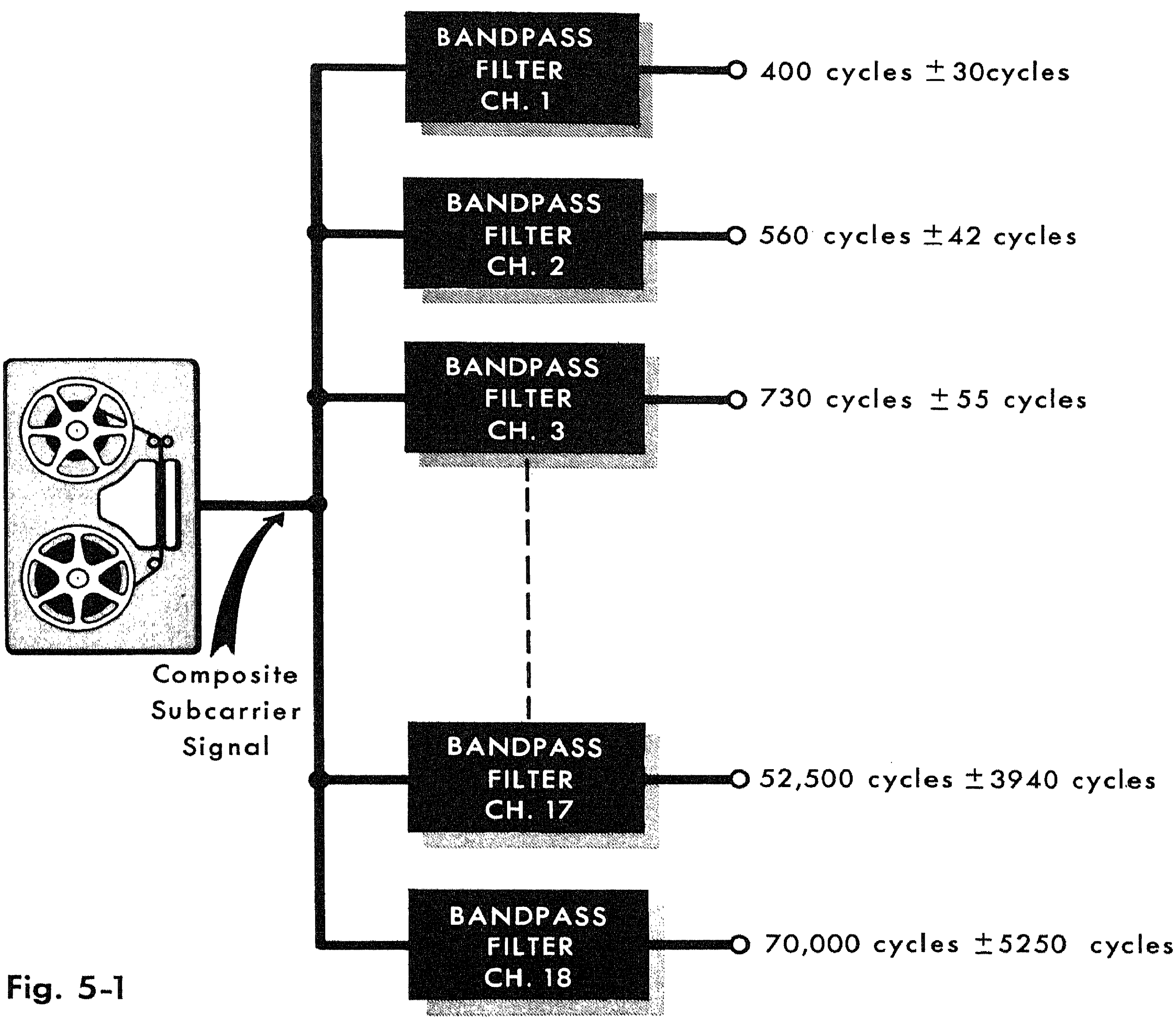


Fig. 5-1

time the input signal crosses the zero axis going negative. (The pulses could just as readily be developed each time the input signal crosses the zero axis in a positive direction—it is a matter of choice for the design engineer.) Following the axis-crossing pulse circuit, the pulses are applied to a delay line or similar delay circuit to produce delayed pulses. The

THE ACTION OF A BASIC PULSE-AVERAGING CIRCUIT

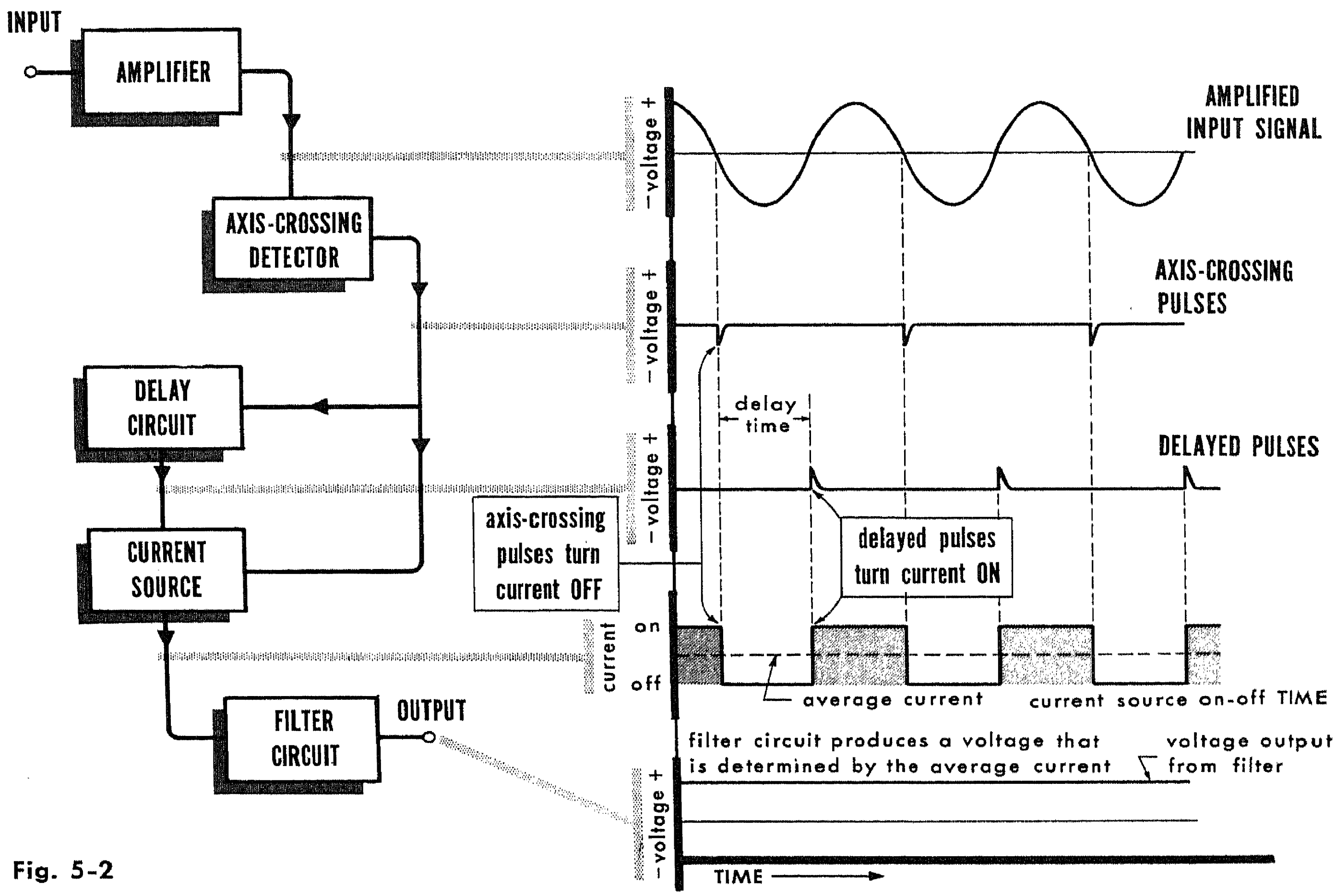


Fig. 5-2

delayed pulses shown have been delayed half a cycle, placing them midway between the axis-crossing pulses. (The delay of 50% is arbitrary; some circuits use a value as high as 90% of a center-frequency cycle delay time.)

Both the axis-crossing pulse and the delayed pulse are supplied to a current source—usually a tube with carefully regulated voltages applied to it. When the tube conducts, a precise amount of current flows. The delayed pulses turn the current source on; the axis-crossing pulses turn the current source off.

Figure 5-3 shows the relationship of signal frequency to the on-off time of the current source and the resulting output voltage. This output voltage is proportional to the frequency. As shown in Fig. 5-3, a lower frequency results in the current source being on for a longer period of time. Conse-

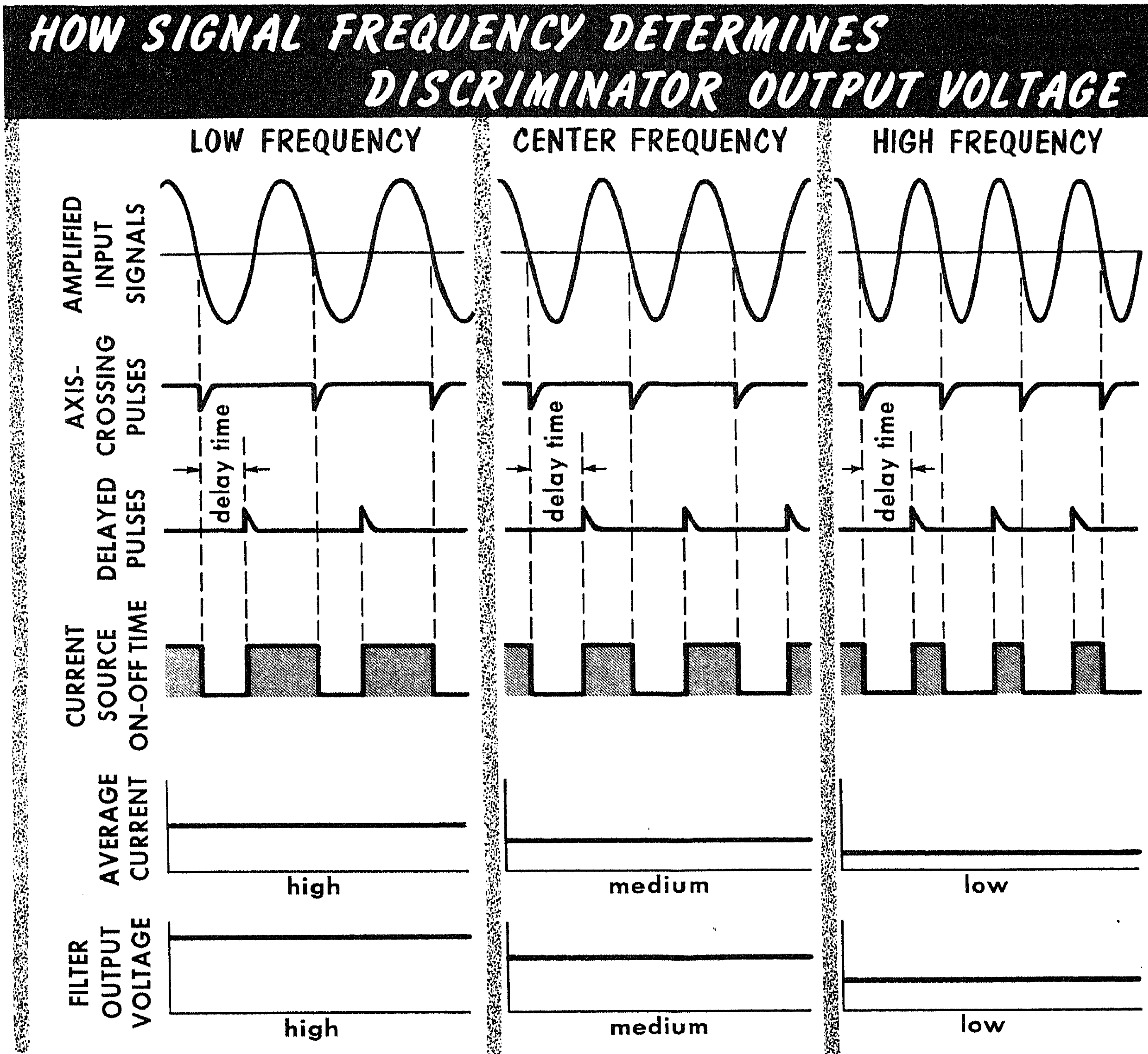


Fig. 5-3

quently the average current of this increased length of time is converted to a larger output voltage. The higher frequency results in a smaller average current due to the reduced length of time, yielding a smaller output voltage.

At the output of the discriminator, the resultant signal is a duplicate of the signal output of the transducer used in the missile. With many different frequencies in use, all higher than the output frequency of the discriminator, some are bound to leak through to the output signal. These unwanted frequencies can create difficulties in the equipment used to indicate the values of the output signal. To remove this interference, a low-pass filter of resistance-capacitance (R-C) or inductance-capacitance (L-C) design is placed at the output of the discriminator. The low-pass filter passes the

discriminator output frequencies, but it blocks all the unwanted higher frequencies. For example, the low-pass filter for Channel 1 is designed with a cutoff frequency of 6 cycles, that for Channel 2 with a cutoff frequency of 8.4 cycles, etc. The interference-free signal, at the output of the low-pass

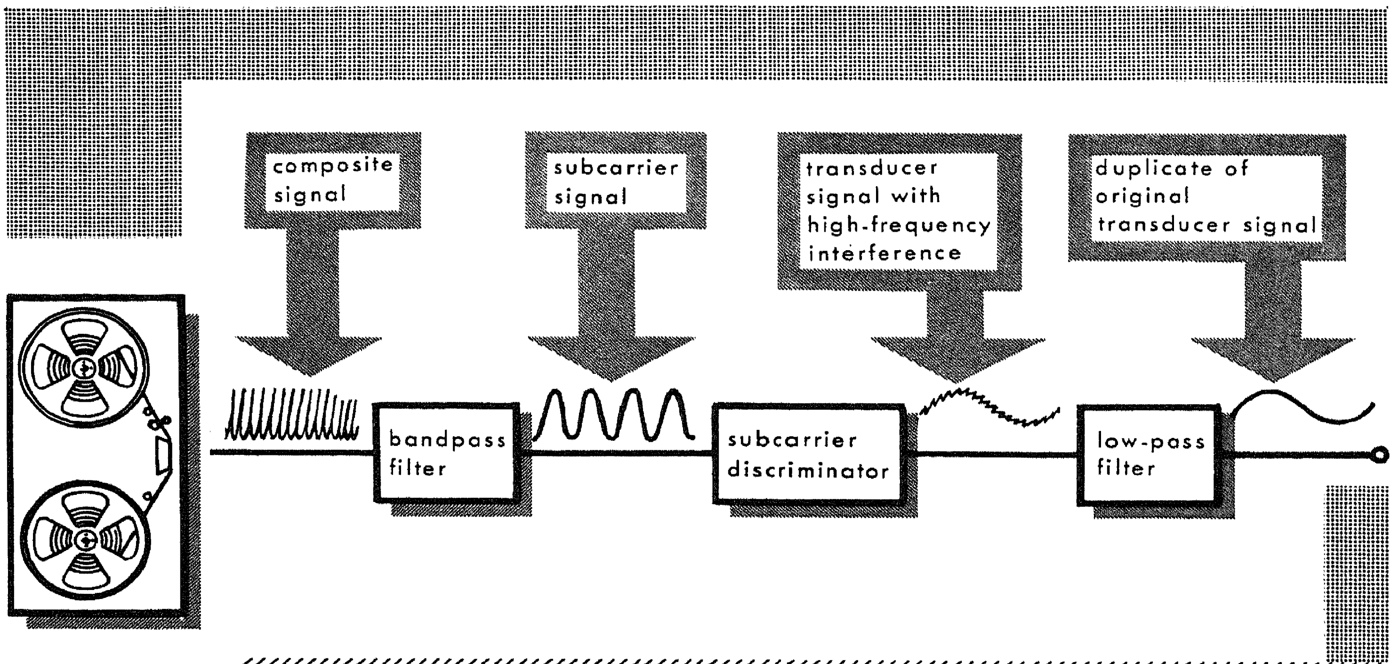


Fig. 5-4 The SIGNAL PATH from the MAGNETIC TAPE to the OUTPUT of LOW-PASS FILTER

filter (Fig. 5-4) represents what transpired at the particular measurement point during the missile flight. This information is now available to indicating devices that engineers and technicians use to decipher it.

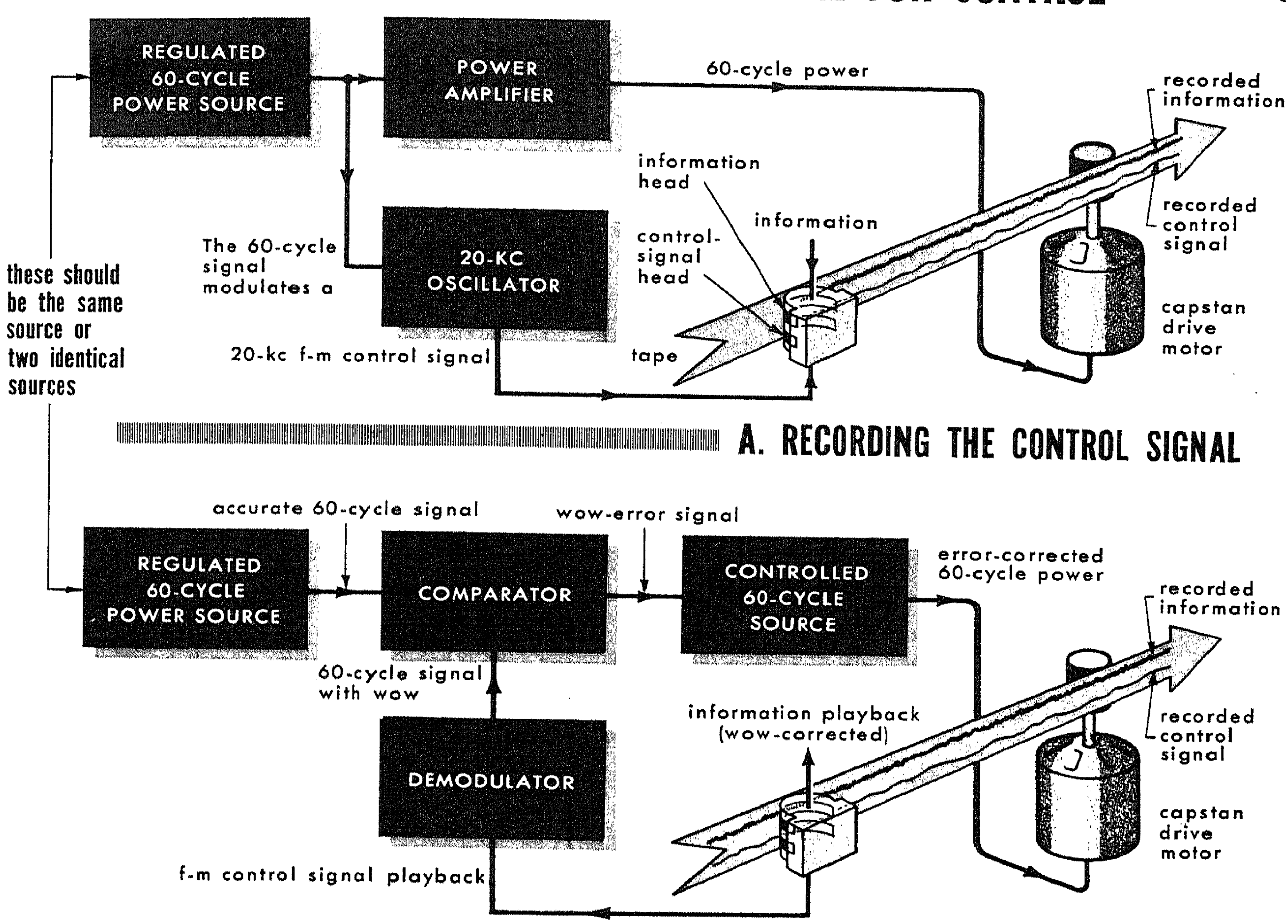
Wow and Flutter Compensation

As mentioned in the discussion of tape recorders, if the tape-drive speed mechanism is not perfect, variations in the tape speed (wow) will result. As the tape goes by the record-playback head, it may move closer or further away (flutter). Wow and flutter result in modulation of the signal applied to the recording tape. The error caused by wow and flutter can be appreciable. At the center frequency of Channel 12 (10,500 cycles), a 1% error is equal to a change in the recorded signal of 105 cycles. This in turn can result in an error high as 8% in the information signal at the output of the discriminator. To overcome these errors, electronic compensation circuits are used. (Electronic circuits operate at speeds sufficiently fast for their control to be considered instantaneous.)

One wow-correction system is incorporated within the tape-recorder console. It requires that the recording and playback be done with the same

unit, or that two identical units be used if the tape-recorder consoles are at separate locations. The recording system, as shown in Fig. 5-5A, uses a regulated 60-cycle power source to drive a power amplifier, which in turn powers the capstan-drive motor. The regulated 60-cycle source amplitude-modu-

WOW-COMPENSATION SYSTEM THAT USES A RECORDED SIGNAL FOR CONTROL



A. RECORDING THE CONTROL SIGNAL

Fig. 5-5 B. USING IT FOR COMPENSATION DURING PLAYBACK

lates a precisely controlled oscillator. (A typical frequency for the oscillator might be 20 kc.) The amplitude-modulated signal is then placed on a separate track of the recording tape, called the control track. Any variations in tape speed (wow) will result in frequency-modulation of the signal on the control-track as well as the original composite signal on another tape track.

At playback, as shown in Fig. 5-5B, the signal of the control track is applied to a demodulator circuit. The demodulator removes the 20-kc signal, leaving the 60-cycle reference signal, which has been frequency-modulated by the

wow. The error-modulated signal is then compared to a regulated 60-cycle source identical to the one used in the recording process. Any difference between the two 60-cycle signals creates an error signal that is representative of the wow error. The error signal is then applied to control the 60-cycle source that is used to power the capstan-drive motor.

As a typical example of correcting an error by this system, a tape recording may be assumed to have contracted due to a temperature difference between the localities in which the tape was recorded and played back. This results in an apparent increase in tape speed. The error signal produced by the control track varies the frequency of the power applied to the capstan-drive motor. This correction decreases the tape speed, restoring the information signal to its original frequency.

A typical method of flutter correction uses a precisely regulated oscillator frequency of 100 kc (occasionally a frequency of 93 kc or 50 kc is used). This reference-frequency signal is applied to the magnetic tape, sometimes on a separate track but more often on the same track as the composite signal. (To do this, the reference frequency must be higher than the highest subcarrier-channel frequency in use.) The 100-kc reference frequency is often designated as Channel K. To use the Channel K reference signal with pulse-averaging discriminator systems, an additional band-pass filter is used at playback to separate the 100-kc frequency from the composite signal (Fig. 5-6). The reference signal, frequency-modulated by flutter in the tape-transport unit, is applied to a frequency discriminator, identical in operation with the pulse-averaging discriminators already discussed. (The output of the flutter-frequency discriminator uses a low-pass filter, as do the discriminators for the subcarrier-channel frequencies.) The output signal of the flutter discriminator is an error voltage that is positive or negative by an amount proportional to the flutter error. A typical output value might be plus or minus 6 volts for each percent of error (1 kc change in the reference frequency).

In a pulse-averaging discriminator using the delayed pulse-type circuit, the error voltage is applied to the current source. Changes in tape speed caused by flutter vary both the composite signal and the 100-kc flutter signal to the same extent, hence the error-voltage output of the flutter discriminator is a true representation of the error of each subcarrier frequency. This error voltage is applied to vary the current source of each subcarrier discriminator. The output of the discriminator is therefore compensated, providing a signal that is relatively free of flutter errors.

For flutter compensation to be effective with the pulse-averaging type of discriminator circuits, the error-voltage output of the flutter discriminator must be applied to the subcarrier-channel discriminator at precisely the correct time. As shown in Fig. 5-6, both signals must coincide at the subcarrier-channel discriminator. At first glance this would seem an easy task; however, the bandpass filters used to separate the subcarrier-channel fre-

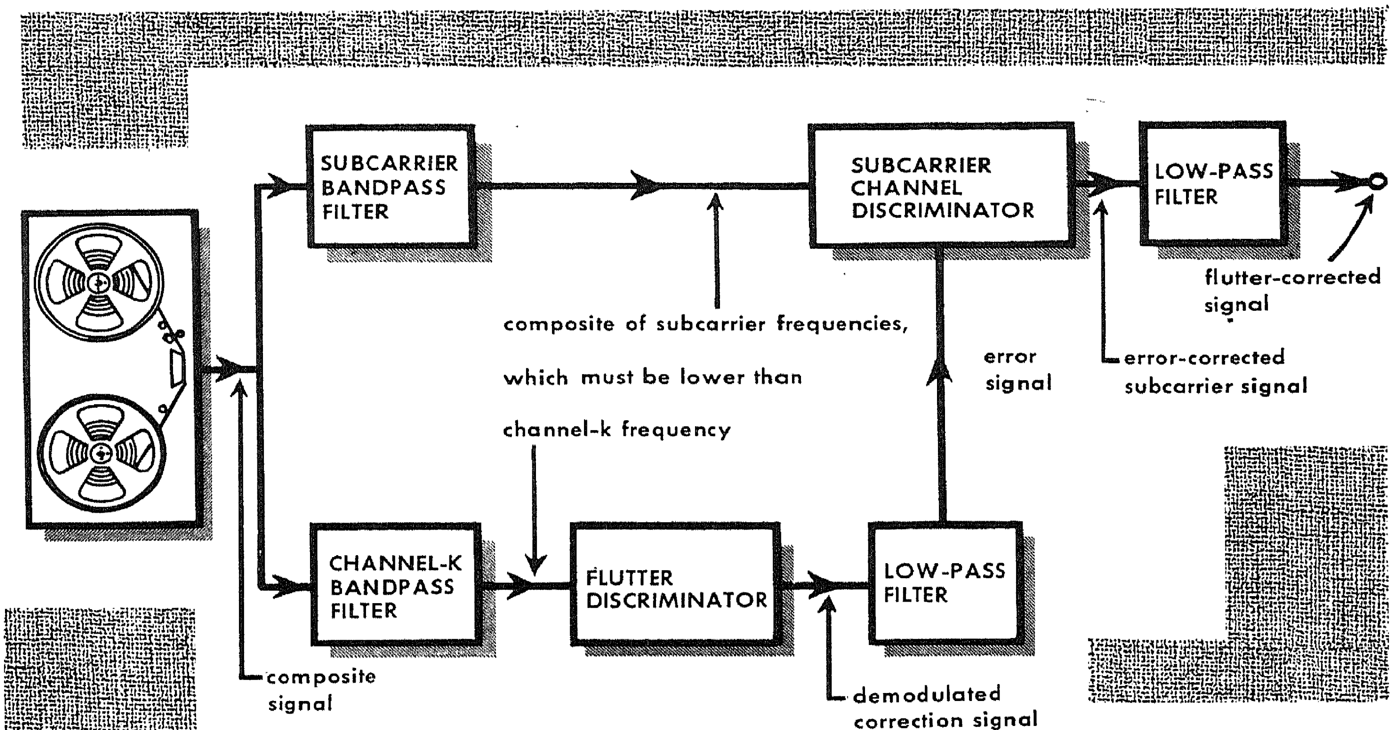


Fig. 5-6 **A FLUTTER-CORRECTION SYSTEM**

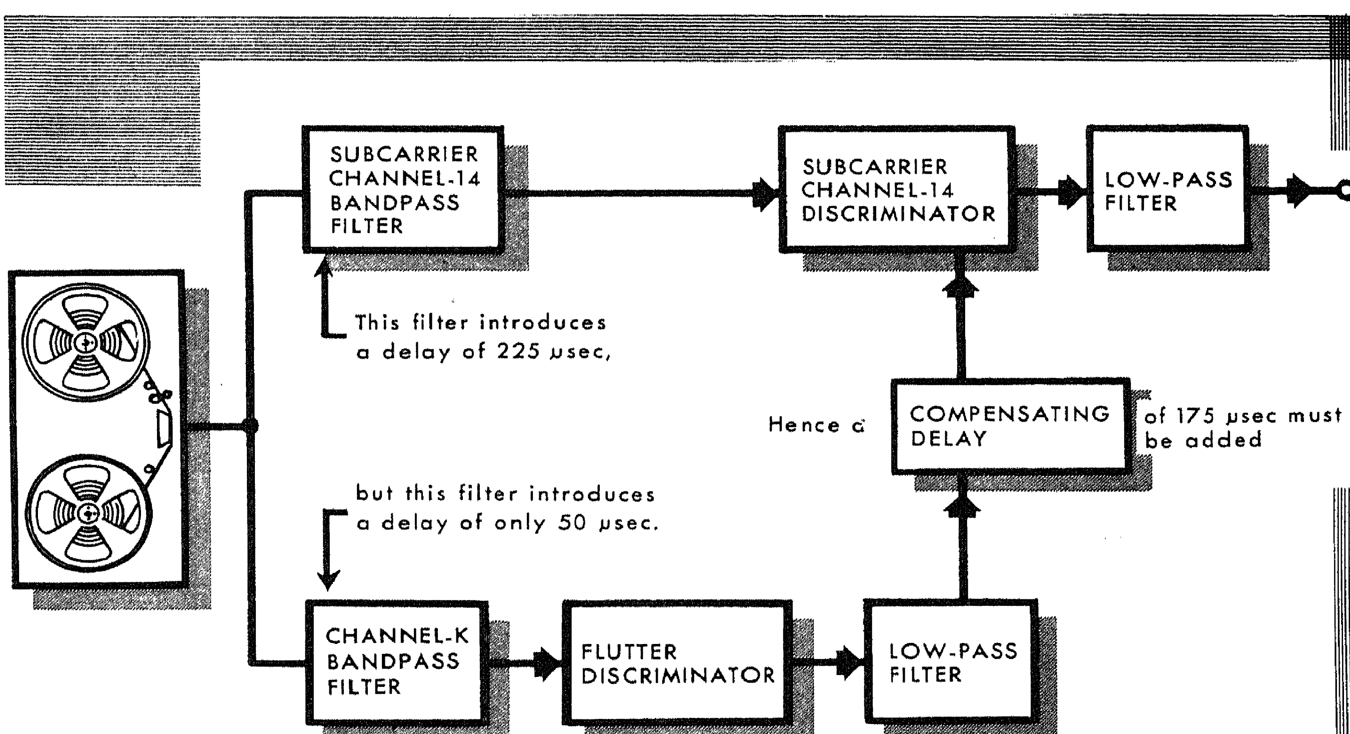


Fig. 5-7 **ADDING A COMPENSATING DELAY FOR CORRECTION ON A SPECIFIC CHANNEL**

quencies and the wow-and-flutter reference frequency interfere. The tuned circuits used to filter the selected frequencies also act as delay circuits. The various delays of the different bandpass filters cause the signals to arrive at different times.

A typical approximation of the delay introduced by a bandpass filter might be to multiply by 5 the time for one cycle of the center frequency of the subcarrier-frequency channel in use. Consider the subcarrier frequency of Channel 14 and the 100-kc frequency of Channel K: The center frequency of Channel 14 is 22 kc. One cycle at 22 kc takes 45 μsec. Multiplying 45 μsec by 5, the result is 225 μsec. For Channel K, the time for one cycle is 10 μsec, which multiplied by 5 is 50 μsec. The difference between the delays imposed by the filters is 175 μsec. This means that the signal being applied to the subcarrier-channel discriminator will arrive 175 μsec after the flutter error signal. To correct this, a 175-μsec delay is introduced in the error-voltage line before the subcarrier-channel discriminator (Fig. 5-7). As a result of the compensating delay, the two signals coincide at the discriminator, yielding a flutter-free output.

PAM-PDM Decommutation

The information carried by PAM or PDM systems usually requires a high information-carrying subcarrier channel. Often Channel E is used because of its maximum information-carrying capabilities. To remove the information contained in a PAM signal, some form of decommutation must be used. The decommutator must also be capable of being synchronized. Since a mechanical switch would have too much inertia for proper synchronization, an electronic switch, which is more versatile and is readily synchronized, is used.

We have already mentioned that the first pulse is the information from the first transducer, the second pulse is information from the second transducer, etc. Using 30 samples per frame as an example for PDM, two samples are used for synchronizing purposes. The last pulse containing information is the 28th pulse. To break this down, many systems are in use—the ingenuity of the engineer is the only limiting factor. The output signals may be presented in either of two manners: providing *serial* output (which means that the outputs will follow one after the other in succession) or providing *parallel* output (which means that all the outputs are available at one time).

The system shown in Fig. 5-8 yields parallel output signals. The subcarrier output signal from the bandpass filter is applied to both a pulse selector and 28 discriminators. The pulse-selector circuits generate pulses for the 28 consecutive samples of information plus a pulse for synchronization. The output of the pulse selector is applied to the gate generator. Referring back to the missile, one information sample is set as a reference for a continuous maximum, or 100% information output. This sample, at the

decommutation system, is applied to a drift compensator, which determines any drift from the 100% reference-information sample. Any drift results in an error-signal output that is applied to the gate generator.

The gate generator controls the 28 output channels. This is done by having the gate-generator circuits pass switching information to the 28 discrimi-

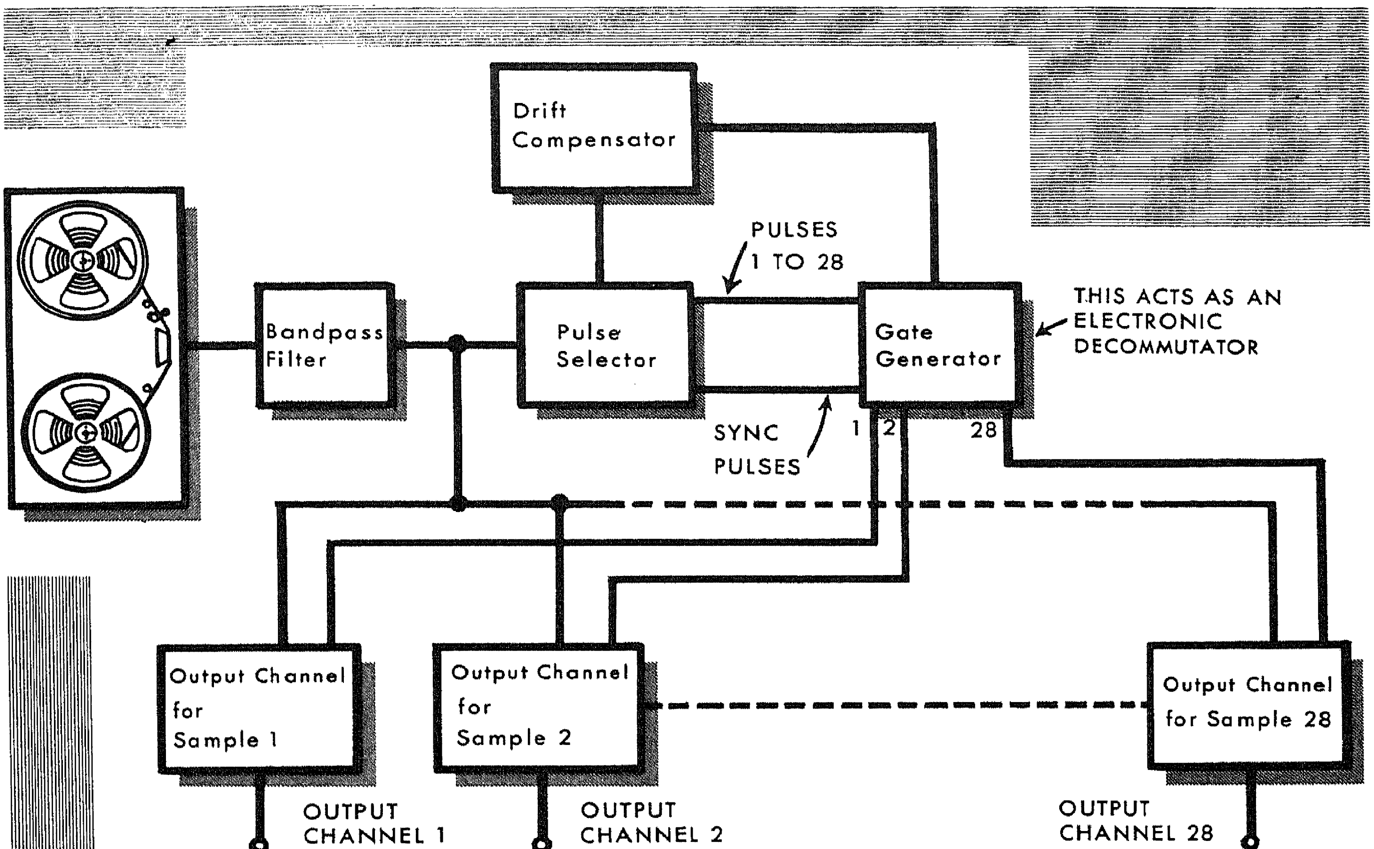
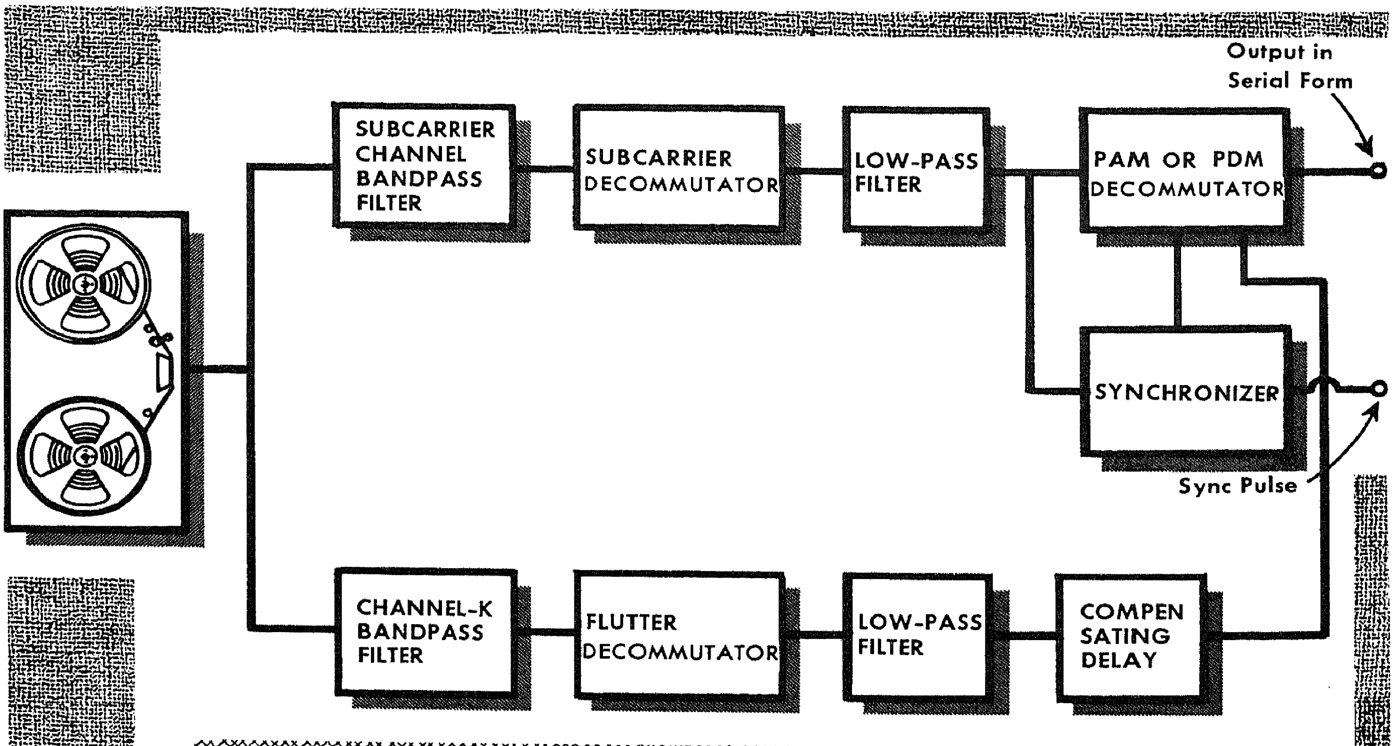


Fig. 5-8

A PAM or PDM Decommutation System That Provides Parallel Outputs

nators, switching them on and off in succession. The error signal from the drift compensator is applied to the gate generator, to correct the time of switching, compensating for any error in the input signal.

The output channels are designed to convert changes in either pulse amplitude or pulse width to equivalent voltage changes, depending upon the system in use. The output voltage level of each output channel is held constant in a storage circuit for adaptability to various types of read-out equipment. At the end of each frame, the stored charge (usually held in a capacitor) is discharged, allowing the new information to reset the output voltage level.



A PAM or PDM Decommutation System That Provides Serial Output

Fig. 5-9

A FIVE-CHANNEL MULTIPLEXER

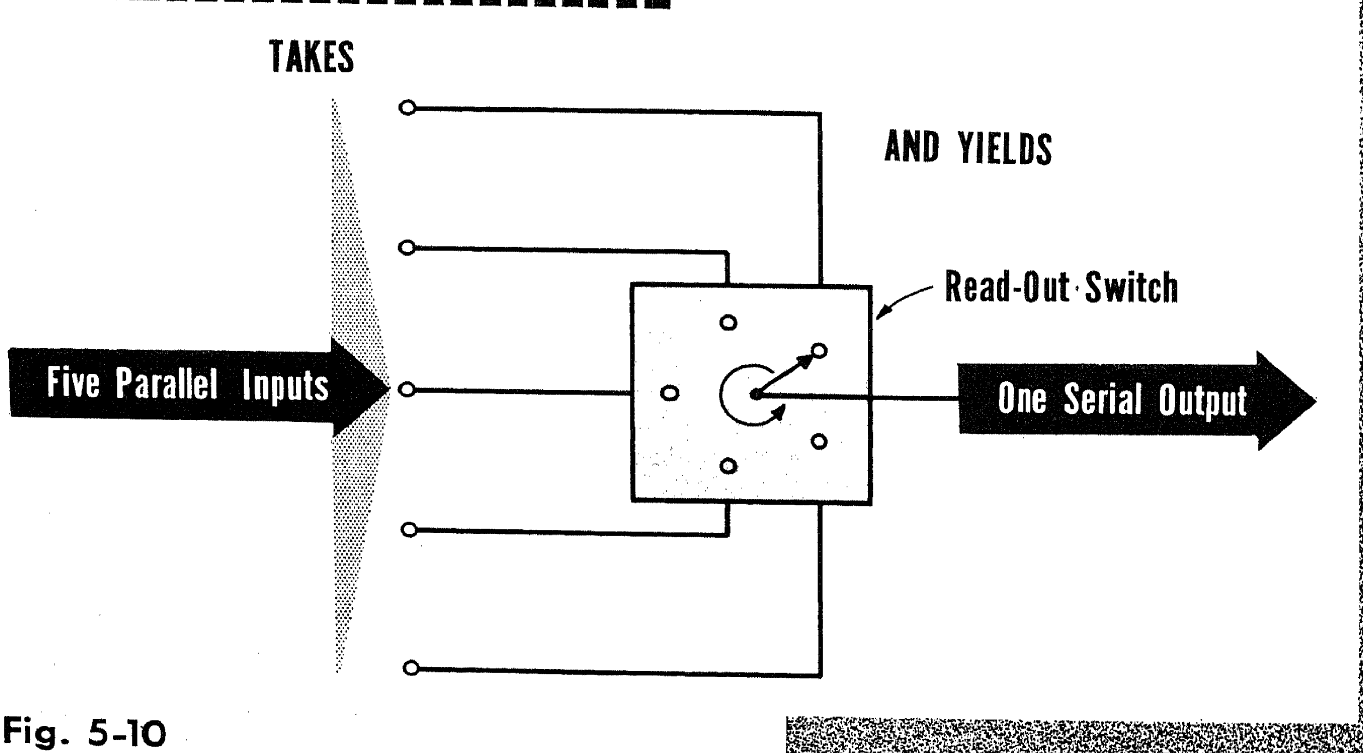


Fig. 5-10

The system shown in Fig. 5-9 provides serial output signals. The composite signal is applied to both the subcarrier bandpass filter, and the flutter reference-frequency Channel K bandpass filter. The subcarrier signal output from the bandpass filter is applied to a subcarrier output channel and low-pass output filter, recovering the original PAM or PDM signal. The PAM or PDM signal is applied to both an output channel and a synchronizer. The output channel, designed for either PAM or PDM, converts each succeeding pulse of information to a corresponding output voltage. The synchronizer is essentially an electronic switch that turns the output channel on for each succeeding information pulse. In addition, it turns the output channel off for synchronization, as well as making the sync pulse available to operate any external equipment. Since the PAM or PDM signal may be stretched or compressed by wow and flutter, the wow-and-flutter error-compensating signal is applied to the PAM or PDM output channel.

The Multiplexer

Quite often it is desired to apply the parallel outputs of a decommutated signal to a single read-out device. Multiplexing is again used, this time in the form of an electronic switch (Fig. 5-10). The multiplexer is usually designed to handle an appropriate number of inputs or channels. By electronic switching, the output of each channel is applied successively to a read-out device. The duration of time in which the channel information is applied to the read-out device is set by the speed of the switch.

A fast-acting read-out device may be confronted with the problem of attempting to read a changing signal value. To prevent this, a *sample* and

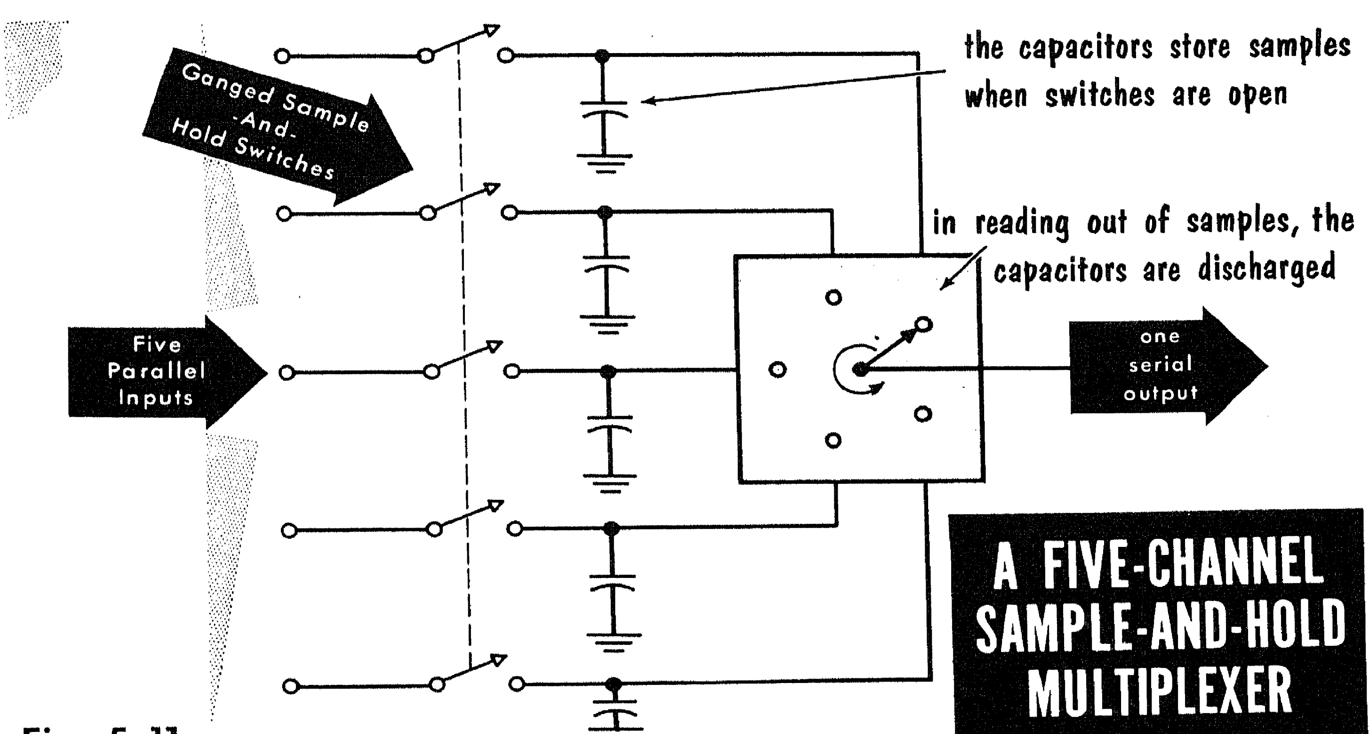


Fig. 5-11

hold multiplex circuit is used. As shown in Fig. 5-11, the parallel information of each channel is applied to a capacitor. After a duration of time just sufficient to charge the capacitor to the level of the input signal of each channel, ganged switches disconnect the inputs from the capacitors. The multiplexer then successively switches to each *sample* of the input signal of each channel, providing a serial output. Meanwhile, the capacitors are in a *hold* condition. (The read-out process discharges the capacitors.) Following the read-out of the last channel, the switches close, and the procedure is repeated.

Recording Instruments

The output of the various types of discriminators or the multiplexer is the signal that tells the engineer what happened during the various functions and phases of the missile. The transducer outputs have been redeveloped, and if all went well, will be exact duplicates. The signal must now be recorded in a form that can be easily interpreted, stored for future reference, or merely glanced at for check-out and editing purposes. For this, use is made of recording instruments that have three main features:

(1) An indicating device that converts the electrical signal variations to equivalent mechanical variations of a pen or similar marking device.

(2) A continuous roll chart of paper or other recording medium upon which to place the signal.

(3) A timed motor drive continuously moving the paper, to reproduce the constantly changing signal.

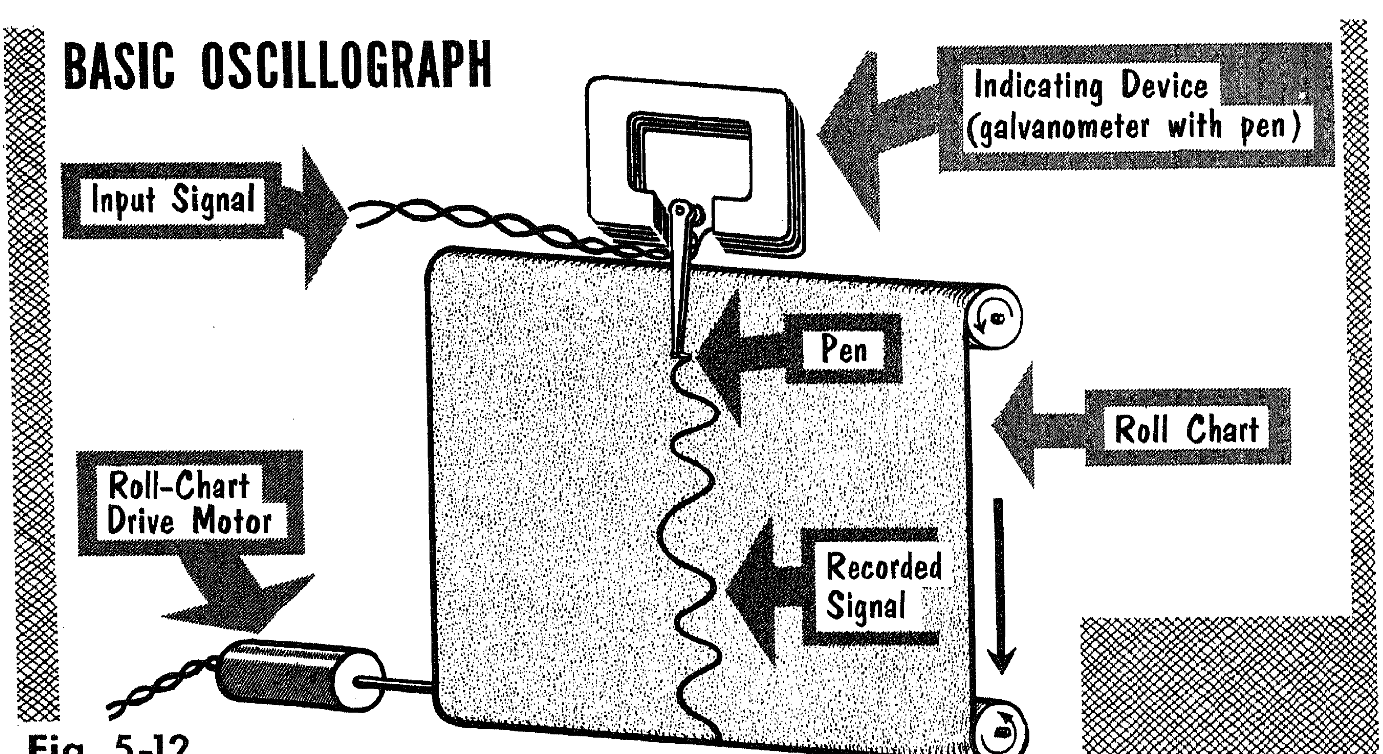


Fig. 5-12

The name for this type of recording device is *oscillograph*. An oscillograph differs from an oscilloscope, in that oscilloscope reproduction is a temporary, fast-changing picture, whereas an oscillograph (Fig. 5-12) writes the pattern for a permanent record.

The chief problem of all oscillographs is the frequency response of the indicating device, which determines how high a frequency it can reproduce. The speed of the paper-roll chart determines the resolution (time per cycle) of the reproduced signal. Should the pen move at too fast a rate relative to the chart, the signal will have crowded overlapping lines. The speed of the roll chart is usually varied by placing a gear train (transmission) between the motor and the driven end of the roll chart. To vary the speed, a gear shift is used. Typical paper speeds may vary from as low as ¼ inch per second to as high as 25 inches per second. The capacity of the roll chart in available recording time is directly related to the roll-chart speed. Obviously, the fast-moving roll chart will be used up quickly, requiring frequent replacement. The thickness and type of paper used determines to a large degree the number of feet in a roll chart. Typical values are 200, 250, 400, and 500 feet. Occasionally the speed of the roll chart is rated in millimeters per second, instead of inches per second.

The resulting output signal plotted on the roll chart shows data versus time. To aid in plotting the time, different methods are used. One method is to use paper with lines divided into values that may be readily converted

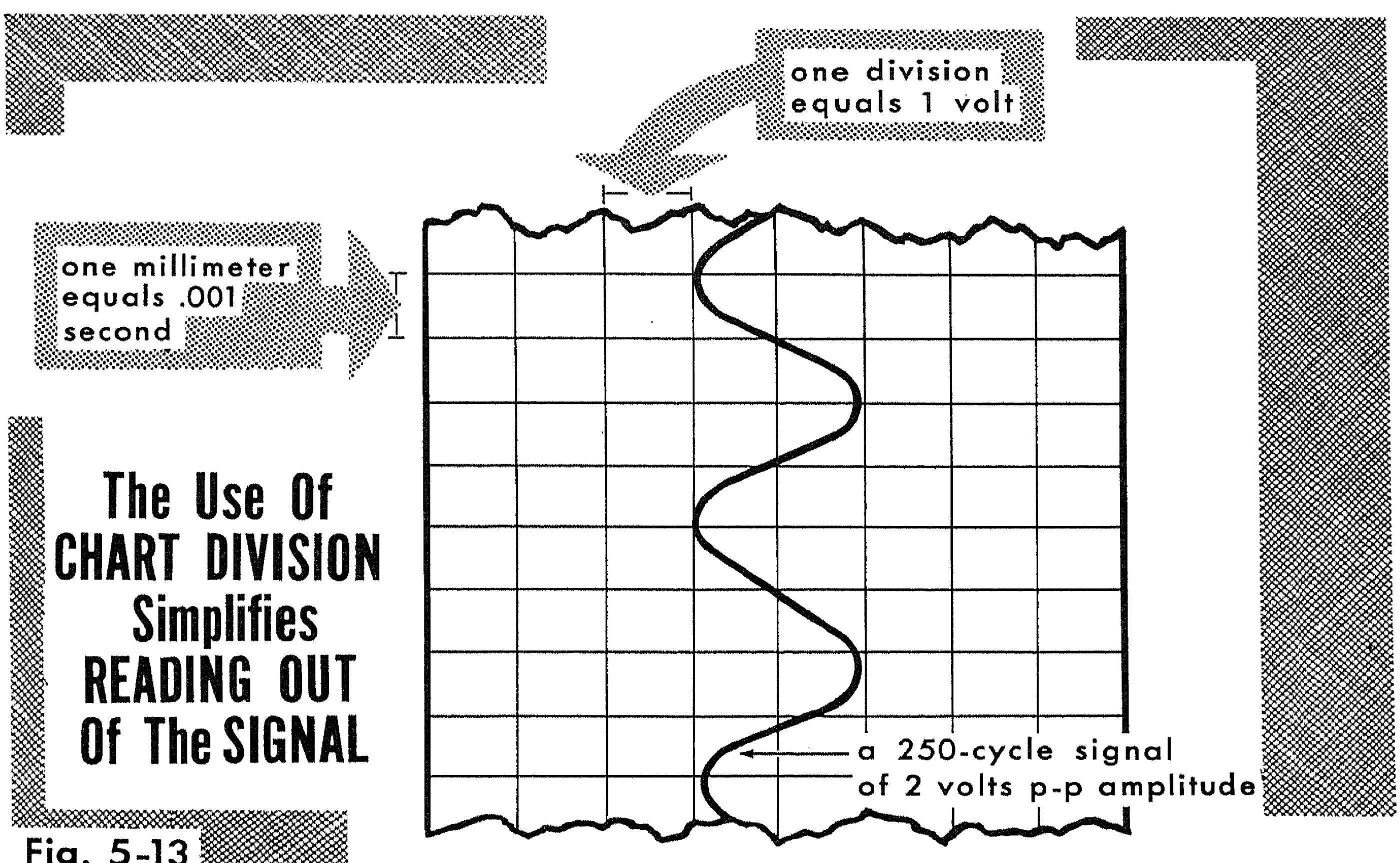


Fig. 5-13

to time, such as ¼ inch equals 1 millisecond, etc. Another method is to use a separate pen called a timing pen, and apply a steady reference frequency to the pen, resulting in a timing marker being applied to the paper. The timing marker is usually read off in values such as 1/10th of a second, 1/100th of a second, etc. The paper-roll chart is printed with divided lines running both across and along the length of the paper. (The lines running the length of the paper indicate signal-amplitude value.) The use of the dividing lines for quick read-out of data is shown in Fig. 5-13.

Reading out of the various channels of information requires either numerous oscillographs or an oscillograph with numerous recording devices. The latter method is doubly advantageous in that quick side-by-side compari-

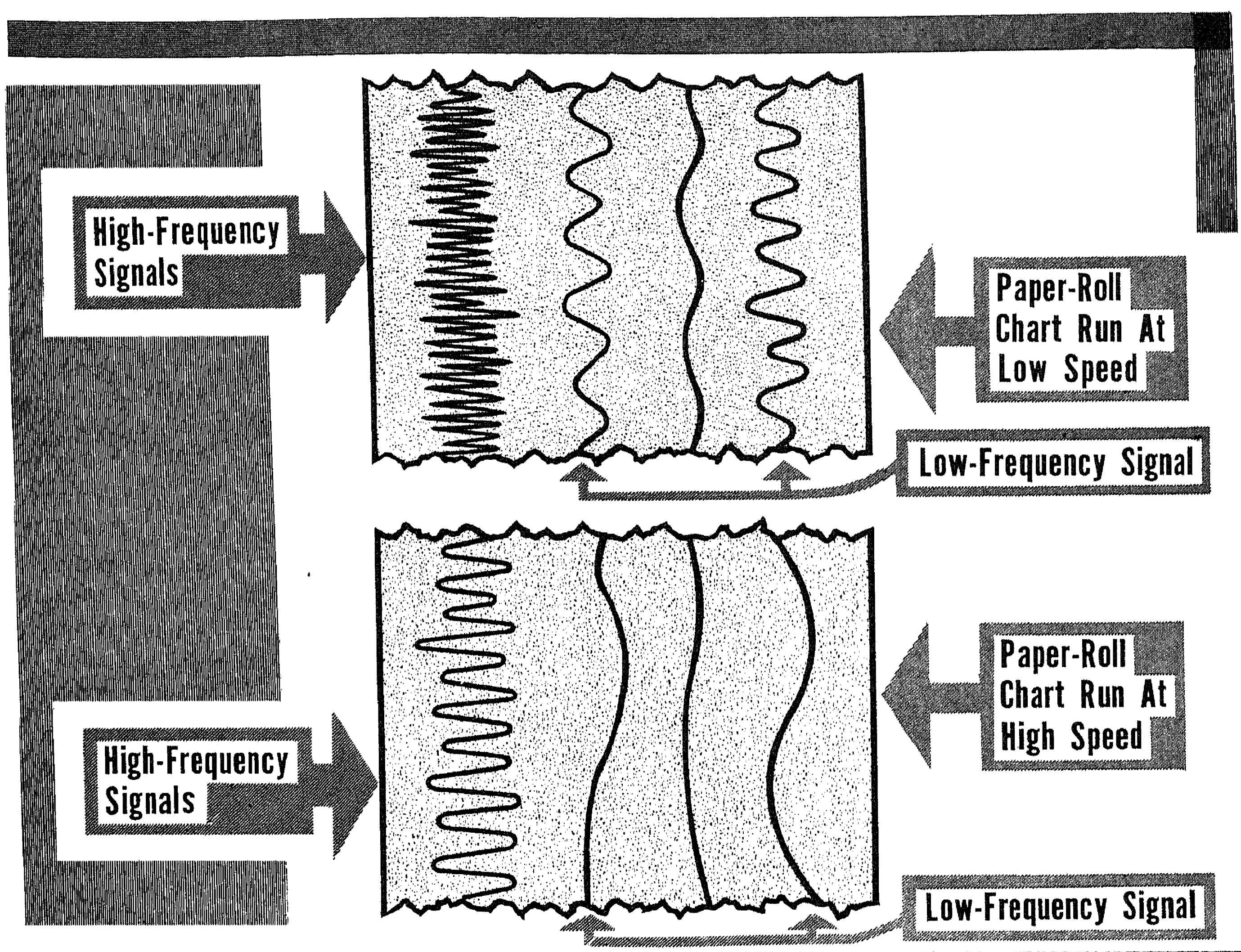


Fig. 5-14 CHART SPEED AFFECTS APPEARANCE OF REPRODUCED SIGNAL

sons of channels may be made. The number of recording devices available varies with the design of each unit—some have as many as 50. A disadvantage in using a multiple-recording device is in its performance when a high-

frequency signal is being read out in conjunction with other low-frequency signals (Fig. 5-14A). Reading out the high-frequency signal requires a fast-moving chart to spread out the signals, which results in spreading out the lower-frequency traces to abnormal lengths (Fig. 5-14B). A compromise is to place the high-frequency signal on a separate oscillograph.

The four most prominent types of recording devices are:

(1) Pen and ink upon paper.
(2) Hot stylus upon coated paper.
(3) Light-beam upon photosensitive paper or film.
(4) Teledeltos (electrosensitive paper).

A major feature of pen-and-ink recording devices is the simplicity of the pen, and the fact that inexpensive untreated paper-roll charts are satisfactory. The pens use various colored inks for coding. A small application of ink to the pen holder provides as much as 12 hours of continuous writing. The oscillograph using a hot-wire stylus upon coated paper works by passing a current through a small length of resistance wire. The result is a *hot-wire stylus,* which is applied to a specially constructed paper. (A thin white sheet of paper is applied over a sheet of black backing paper.) As the paper is passed under the hot stylus, the top layer of specially treated white paper is destroyed by the heat, leaving a sharp clear black trace. As the speed of the paper traveling under the stylus is increased, the heat of the stylus must be increased to be sure that the coating of the fast moving paper is burned away. This is usually done automatically by increasing the current flow through the resistance wire as the paper speed is increased.

The use of a beam of light upon sensitized paper has many advantages—multiplicity of recording devices, high paper speed, and increased frequency response of the indicating device. The indicating device has a small mirror mounted to reflect from a fixed light bulb a sharp spot of light at a fixed point (Fig. 5-15). Deflecting the mirror with the input signal will cause the spot of light to vary directly with the input signal. The light-beam spot is applied to a special paper that may be handled in the open light. When placed in a special holding magazine, it is printed as it unrolls. As the paper is drawn past the moving spot of light, it is exposed only to the area covered by the spot. The paper is then processed as is a roll of photographic film. Some units do the processing inside the oscillograph unit, others have a special magazine to which the exposed paper is removed in a light-proof container, to be processed in a special unit. An advantage of a light-beam oscillograph is that the trace of each light beam may overlap. This cannot be done in a stylus-type oscillograph, where the styli will collide with an overlapping signal. Figure 5-16 shows a light-beam oscillograph in which the paper is processed as it is run off.

A Teledeltos recorder uses an electrosensitive paper and writes directly, requiring no special processing. As the paper is drawn under a fixed stylus, current is passed through both the stylus and paper, burning off a

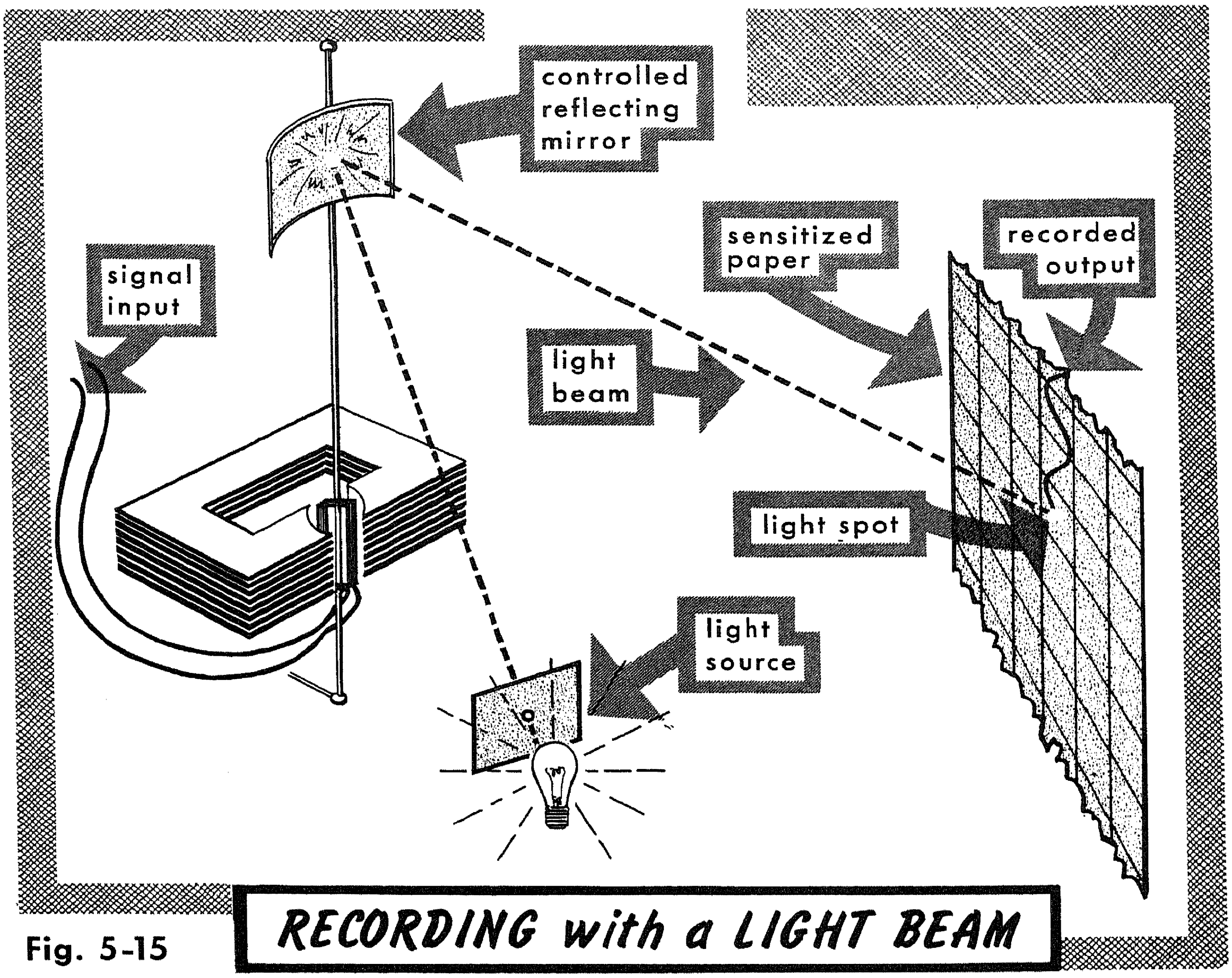


Fig. 5-15

A LIGHT-BEAM OSCILLOGRAPH

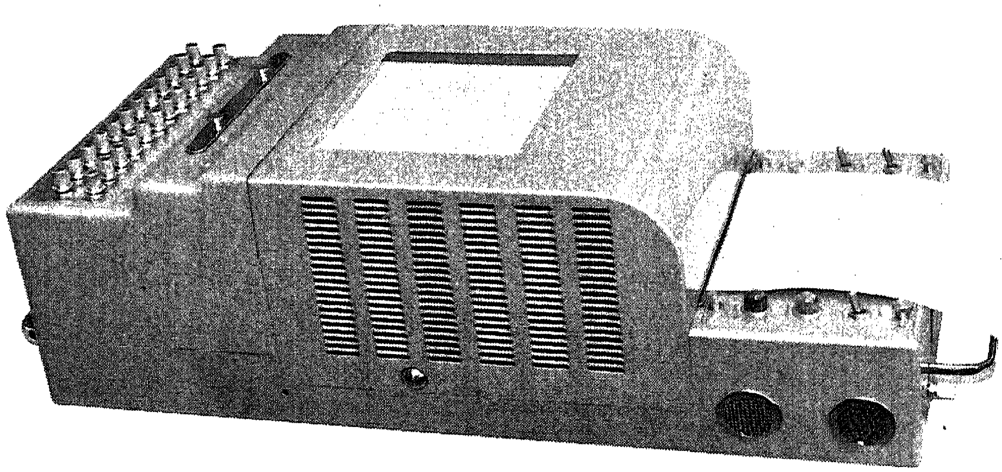
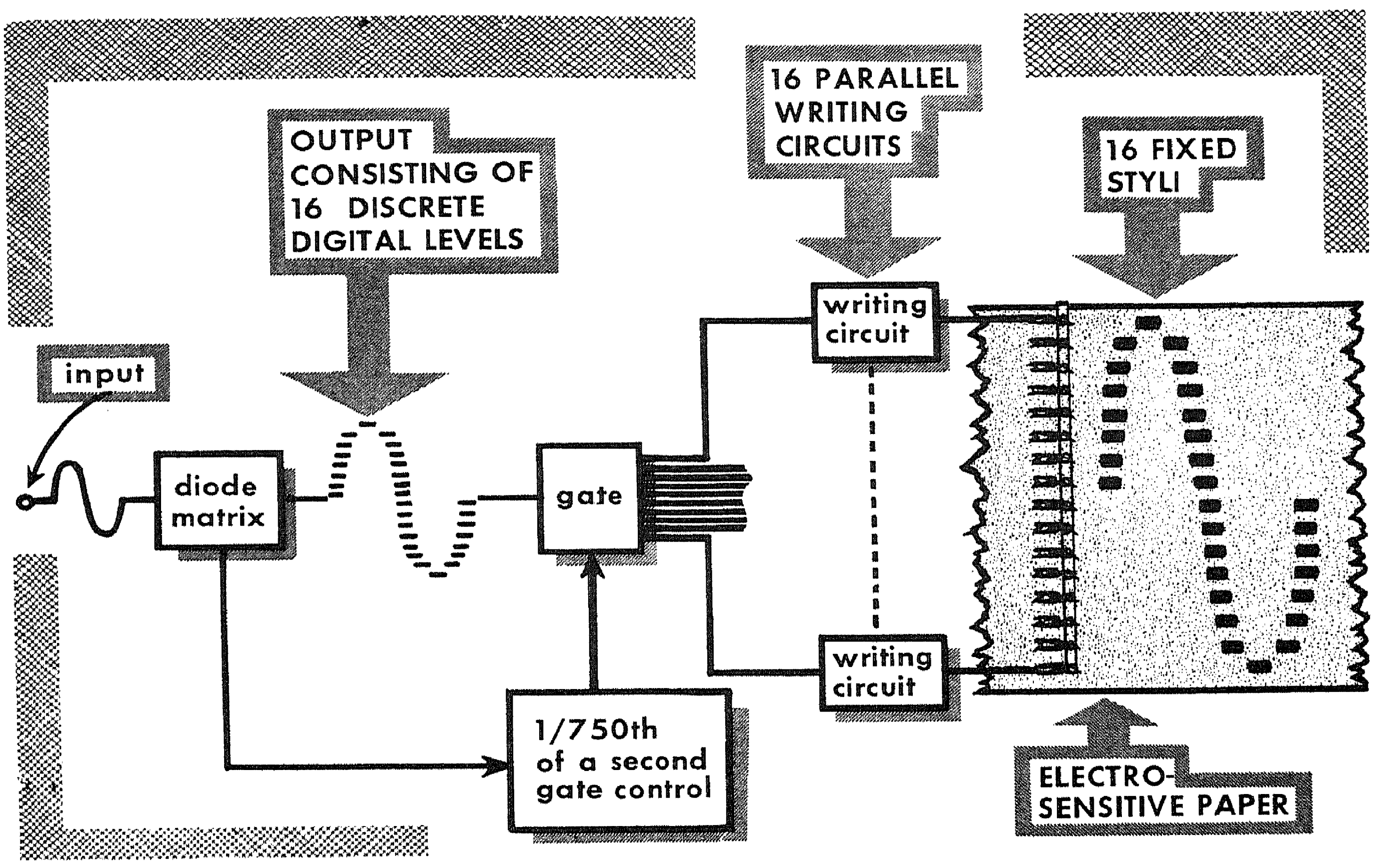


Fig. 5-16 **WITH DIRECT PAPER PROCESSING**

thin top coating of the paper, leaving a black trace. By using many fixed styli placed in a line across the paper chart, and switching the current output to various styli, a reproduction of the input signal will be drawn. The moving parts of pen motors, galvanometers, etc. present a problem in inertia. The use of fixed styli with electronic switching removes this problem. When the signal changes from 0 to 100 percent, there is no overshoot. Fixed styli also permit rugged construction that is relatively unaffected by shock and/or vibration.

The use of a series of fixed styli requires that the input signal be broken down into a series of discrete levels that can provide on-off data to the individual stylus. Figure 5-17 shows a single-channel Teledeltos system. The



A Single-Channel Teledeltos Recording System

Fig. 5-17

input signal is applied to a diode matrix, which divides the input signal into 16 separate outputs representing 16 discrete digital levels. This output is applied to a gate that is controlled by external gate-control circuits. Once each 750th of a second, the gate is opened to permit the 16 digital levels to be applied to 16 writing circuits. (These writing circuits are specially designed amplifier circuits that remain in a cutoff condition, and provide an

amplified output only when a signal is applied to the input.) When each of the 16 styli is provided with an output signal from the writing-circuit amplifiers, current passes through it to provide an indication on the chart. The outputs of the 16 styli closely resemble the original input signal.

One of the problems of using pen and ink reproduction is shown in Fig. 5-18A. The pen swings back and forth upon a fixed radius, but the ouput signal, although a true reproduction of the input signal in value, does not *appear* is a similar signal. Applying a square-wave input signal, the pen starts to swing up. However, its fixed radius causes it to swing to one side. The moving paper chart, plus the fixed radius, result in a *curvilinear* recording that looks like a clipped sawtooth wave.

The hot stylus on a coated-paper oscillograph overcomes this difficulty by using a relatively long hot wire on the end of the stylus. This is used on a

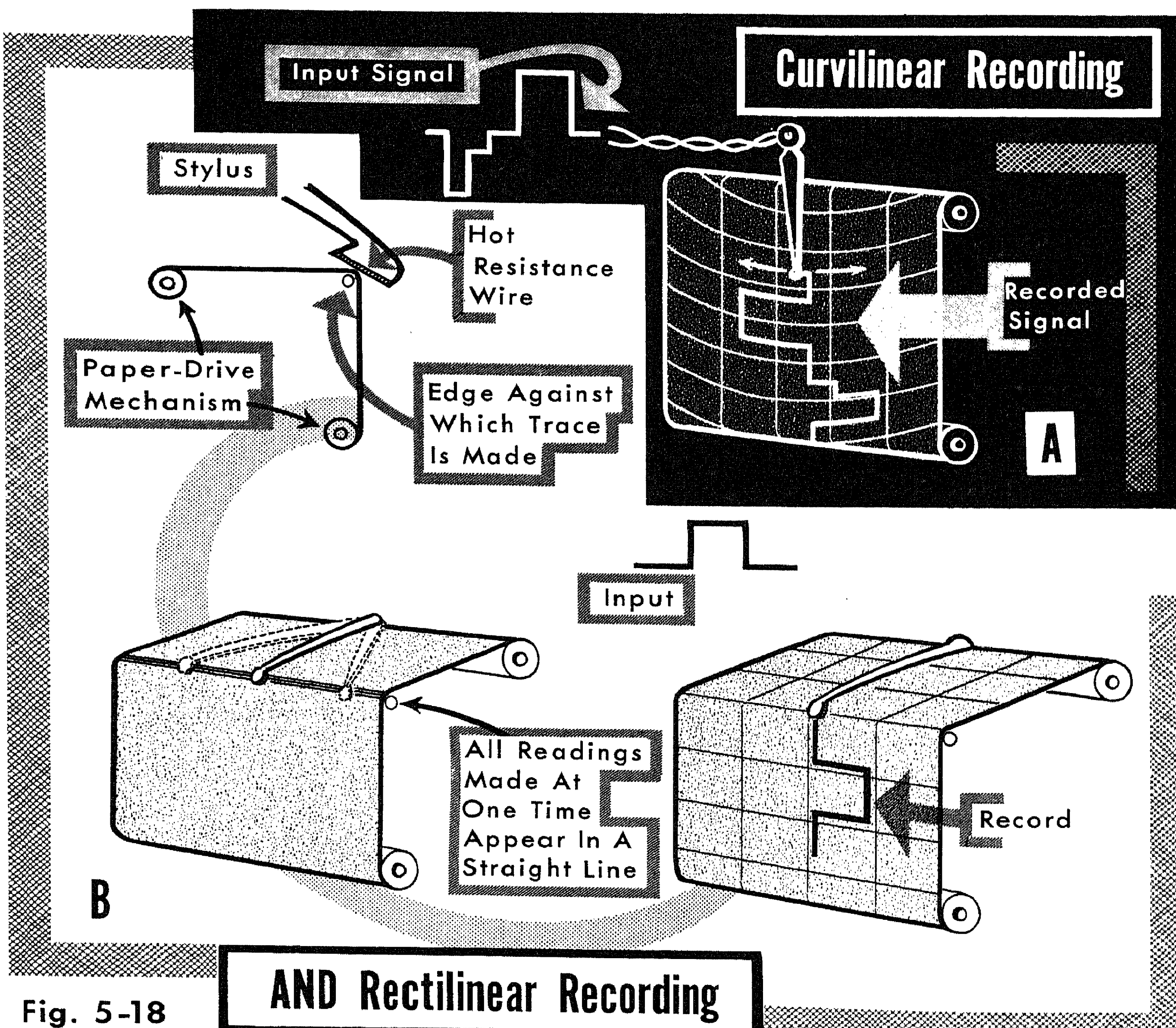


Fig. 5-18

portion of the paper as it is passed over a sharp edge, as shown in Fig. 5-18B. This overcomes the objectionable radius swing, and the resulting *rectilinear* recording is a direct reproduction of the input signal.

The indicating device that drives the stylus, or pen, is called a pen motor. Most often it is a version of a D'Arsonval galvanometer movement, with a pen, stylus, or mirror attached, as already indicated in Figs. 5-12 and 5-15. Applying the signal to the coil, causes it to rotate as in any D'Arsonval movement. As the coil twists back and forth on its suspension, the mirror or stylus twists with it. Galvanometers and other D'Arsonval-type movements are basically d-c instruments, and cannot fluctuate too fast. Typical frequency response for pen or stylus recorders average 20 to 30 cycles, with specially designed units having a frequency response up to 70 cycles. Galvanometers used with a beam of light have a higher frequency response, averaging 1500 cycles, with specially designed units having a frequency response as high as 3500 cycles or more.

Occasionally the galvanometer or other type of pen motor will have as an input a signal with insufficient strength. Amplifiers are then placed ahead of the indicating devices to increase the signal level. These amplifiers are of special design since the lowest frequency to be amplified might be a d-c signal. This rules out the use of ordinary a-c amplifiers.

Quite often a plot is desired of two information signals; instead of reading the data versus time, we may desire to read data versus data. Examples might be to read fuel flow versus fuel pressure or temperature versus altitude. To achieve this, an X-Y plotter (a specially designed oscillograph in which two arms can be moved along tracks or rails) is used. There are various methods of achieving this. In Fig. 5-19, any variation in the Y axis causes the entire support to move up or down on a track, and variations in

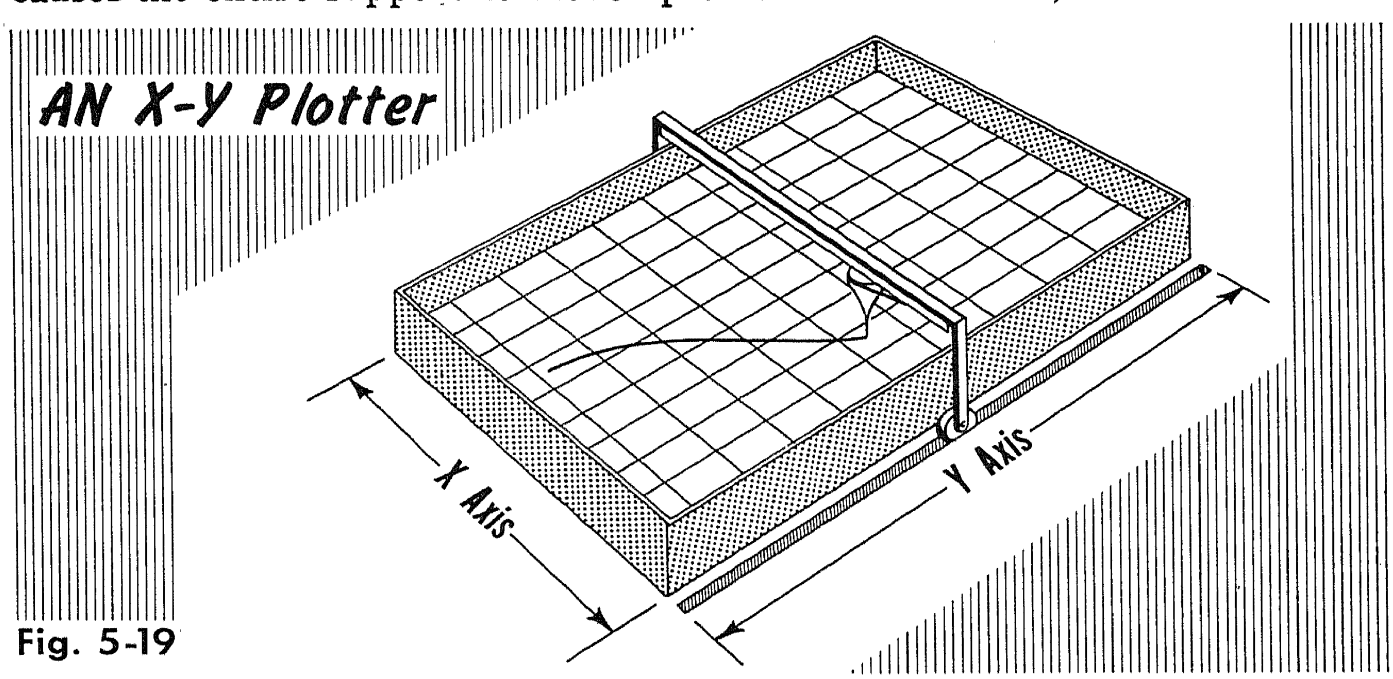


Fig. 5-19

the X axis cause the pen to move left or right along the rail. In X-Y recorders the paper chart is usually a fixed flat sheet that is replaced after the desired information is drawn upon it.

Quick-look editing permits viewing an oscilloscope or an oscillograph to note any major variations, detect faulty information, locate important information, etc. Many transducer outputs are measured for purely monitoring purposes. The information desired in these cases is not how the unit performed, but if it performed at all. Quick-look editing allows the monitoring of these functions.

6. DIGITAL TECHNIQUES IN TELEMETRY

Binary Arithmetic

One of the questions most often asked in telemetry is "How is it possible to place a number on a magnetic tape?" The reply is "Numbers are not placed on tape—symbols in the form of *binary notation* are." (The notation does not *have* to be binary; however, binary notation is best suited for the purpose.) The *binary* system of arithmetic is based on the number 2. (The system in normal every day use is based upon the number 10 and is called the *decimal* system.)

The binary symbols are simply yes or no, on or off, a presence or absence. We can assign a number 1 to a yes, and a 0 to a no. The same holds true for presence or absence; we can assign a 1 to presence, and a 0 to absence. Unfortunately, these associations are not standard. Some firms choose to use opposite signs, so that a yes is 0 and a no is 1. The choice is purely arbitrary, and does not change the end result. But it is important to be sure of the designation in use with the equipment at hand.

The mere yes or no, symbolized by 1 or 0, is not in itself sufficient to make use of binary notation. To aid in understanding the binary system, let us briefly review a portion of the decimal system. To express numbers in the decimal system using powers or exponents of 10, follow these basic rules: Any number expressed to a power of 1 is equal to the number itself. For powers of 2 or more, the number used is multiplied by itself by the number of times expressed in its power. As shown in the table, 10^2 is equal to 10×10, or 100; 10^3 is equal to $10 \times 10 \times 10$, or 1000, etc.

To express a digit such as 3, write 3×10^0, which is equivalent to writing 3×1. To express the number 13, write $1 \times 10^1 + 3 \times 10^0$, which equals $10 + 3$. The number 20 is written as 2×10^1, the number 23 as $2 \times 10^1 + 3 \times 10^0$. The breakdown of a large number such as 4372 becomes:

$$\begin{aligned} 4 \times 10^3 &= 4000 \\ 3 \times 10^2 &= 300 \\ 7 \times 10^1 &= 70 \\ 2 \times 10^0 &= \underline{2} \\ & 4372 \end{aligned}$$

EXPONENTS

USED IN DECIMAL ARITHMETIC		USED IN BINARY ARITHMETIC	
$10^0 = 1$	$10^7 = 10{,}000{,}000$	$2^0 = 1$	$2^7 = 128$
$10^1 = 10$	$10^8 = 100{,}000{,}000$	$2^1 = 2$	$2^8 = 256$
$10^2 = 100$	$10^9 = 1{,}000{,}000{,}000$	$2^2 = 4$	$2^9 = 512$
$10^3 = 1000$	$10^{10} = 10{,}000{,}000{,}000$	$2^3 = 8$	$2^{10} = 1024$
$10^4 = 10{,}000$	$10^{11} = 100{,}000{,}000{,}000$	$2^4 = 16$	$2^{11} = 2048$
$10^5 = 100{,}000$	$10^{12} = 1{,}000{,}000{,}000{,}000$	$2^5 = 32$	$2^{12} = 4096$
$10^6 = 1{,}000{,}000$	$10^{13} = 10{,}000{,}000{,}000{,}000$	$2^6 = 64$	$2^{13} = 8192$

In the binary system, the rules for powers, or exponents, are the same as in the decimal system; however, instead of the number 10, in the binary system we use the number 2. As shown in the second part of the table, 2^2 is equal to 2×2, or 4; 2^3 is equal to $2 \times 2 \times 2$, or 8. To add in a binary system, we go from the least significant digit at the extreme right to the most significant digit at the extreme left. The table of binary numbers is explained as follows:

For the zero, the total is zero.
Number 1 is represented by a yes, or 1, in the 2^0 column.
Number 2 is represented by a yes, or 1, in the 2^1 column.
Number 3 consists of $2 + 1$, therefore we place a 1 in the 2^0 column, and a 1 in the 2^1 column.
Number 4 is represented by a 1 in the 2^2 column.
Number 5 consists of $4 + 1$. A 1 is placed in the 2^2 column for 4, and a 1 in the 2^0 column for 1.
Number 6 consists of $4 + 2$. A 1 is placed in the 2^2 column for 4, and a 1 in the 2^1 column for 2.
Number 7 consists of $4 + 2 + 1$. A 1 is placed in the 2^2 column for 4, a 1 in the 2^1 column for 2, and a 1 in the 2^0 column for 1.
Number 8 being 2^3, a number 1 is placed in the corresponding column, etc.

An example of expressing a number in the binary system is $22 = 10110$
Breaking it down and adding:

2^4 (16)	2^3 (8)	2^2 (4)	2^1 (2)	2^0 (1)
1	0	1	1	0

$$\begin{aligned} 2^4 &= 16 \\ 2^2 &= 4 \\ 2^1 &= 2 \\ \hline & 22 \end{aligned}$$

Thus it can be seen that any number can be expressed in binary form. Let us express in binary form the number, 4372, we used in reviewing the decimal system:

$$\begin{aligned} 2^{12} &= 4096 \\ 2^8 &= 256 \\ 2^4 &= 16 \\ 2^2 &= 4 \\ \hline & 4372 \end{aligned}$$

In binary form:

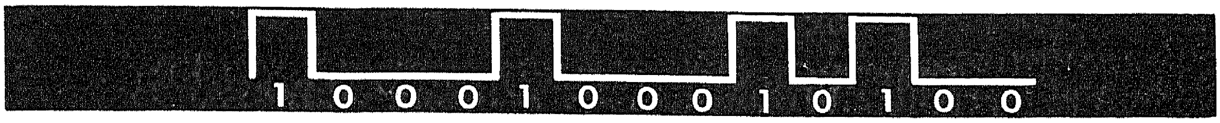
2^{12} (4096)	2^{11} (2048)	2^{10} (1024)	2^9 (512)	2^8 (256)	2^7 (128)	2^6 (64)	2^5 (32)	2^4 (16)	2^3 (8)	2^2 (4)	2^1 (2)	2^0 (1)
1	0	0	0	1	0	0	0	1	0	1	0	0

At first glance the binary number may appear bulky compared to the decimal number. Nevertheless, to place 4372 on a magnetic tape or punched cards would be easy. By converting the 1 or 0 to a yes or no, we may go a step further and say yes or 1 is the presence of a pulse, and no or 0 is the absence of a pulse.

For example:

Yes	No	No	No	Yes	No	No	No	Yes	No	Yes	No	No
1	0	0	0	1	0	0	0	1	0	1	0	0

Converting the binary notation of 4372 to a yes or no pulse equivalent:



The end result is a system that can represent any number merely by the absence or presence of a pulse. Using the binary system, the number 4372 expressed above requires 13 *bi*nary digi*ts*, or *bits*, from 2^0 to 2^{12}. To express the number 7 in binary form (see table of binary numbers), requires a binary system that could express itself to 3 bits. The number 29 requires 5 bits, etc.

BINARY NUMBERS

Number	*Binary Code*					*Number*	*Binary Code*				
	2^4 (16)	2^3 (8)	2^2 (4)	2^1 (2)	2^0 (1)		2^4 (16)	2^3 (8)	2^2 (4)	2^1 (2)	2^0 (1)
0					0	16	1	0	0	0	0
1					1	17	1	0	0	0	1
2				1	0	18	1	0	0	1	0
3				1	1	19	1	0	0	1	1
4			1	0	0	20	1	0	1	0	0
5			1	0	1	21	1	0	1	0	1
6			1	1	0	22	1	0	1	1	0
7			1	1	1	23	1	0	1	1	1
8		1	0	0	0	24	1	1	0	0	0
9		1	0	0	1	25	1	1	0	0	1
10		1	0	1	0	26	1	1	0	1	0
11		1	0	1	1	27	1	1	0	1	1
12		1	1	0	0	28	1	1	1	0	0
13		1	1	0	1	29	1	1	1	0	1
14		1	1	1	0	30	1	1	1	1	0
15		1	1	1	1	31	1	1	1	1	1

Some advantages and uses for binary-number notation are:

(1) Ease in handling since it requires simple on-off pulse-handling circuits.
(2) It is the language of digital computers.
(3) It permits recording numbers on magnetic tape.
(4) Possibility of using bi-stable circuits, such as multivibrators.
(5) Electronic converters read a value of voltage, then convert it to a binary form for expression in binary notation.

Pulse-Code Modulation (PCM)

An important form of telemetering transmission is Pulse-Code Modulation (PCM), based solely on digital techniques. Four advantages of PCM are:

(1) High transmission accuracy—there is no complex signal, it is merely on or off.
(2) Data can be recorded directly on magnetic tape or transmitted.
(3) Superior signal-to-noise ratio (when the signal is above the receiver threshold).
(4) At the ground station the PCM signal may be prepared for direct entrance to a computer.

As shown in Fig. 6-1, the beginnings of PCM are similar to those of PAM. The outputs of the transducers are applied to an electronic commutator, or multiplexer yielding a PAM signal. The various signal voltages are applied to a converter or coder, which converts each voltage reading to its equivalent value in binary form *(encoding)*. The output of the converter consists of binary-coded information denoting the voltage value of the amplitude of each input pulse. After counting each frame of input samples, the frame count is also provided in binary form.

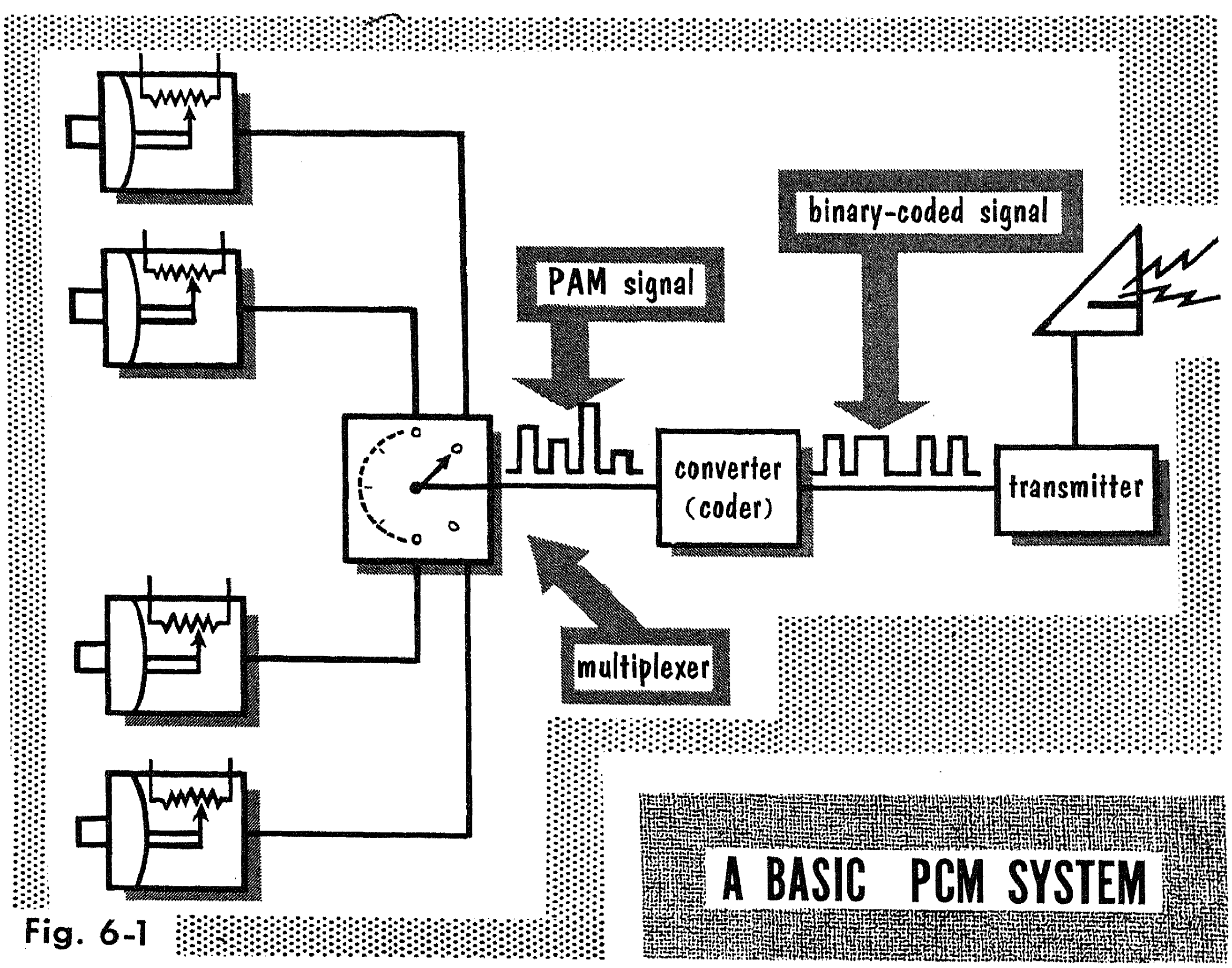


Fig. 6-1

The action of conversion of a voltage to a digital code using one type of converter is explained as follows: Assuming an input voltage of 7.5 volts being applied to a 0-10-volt input range. The input voltage is then changed to an equivalent value of current ranging from 0 to 8 ma at full scale. The value of 7.5 volts, which is ¾ of the input range, is changed to an equivalent value of ¾ of the full-scale-current value of 8 ma, or 6 ma. The input current of 6 ma is then compared with the ½-scale current value of 4 ma. The 4 ma is less than the input value of 6 ma, and is then accepted. (Had it been larger, it would have been rejected.) The input value is then compared with a value that is ½ of the remaining 4 ma, or 2 ma, plus the accepted 4 ma for a total of 6 ma. Since the 6 ma is not greater than the input of 6 ma it is being compared with, it is accepted. The input value is then compared to a value that is ½ of the remaining 2 ma, or 1 ma, plus the accepted 6 ma for a total of 7 ma. The 7 ma is greater than the input of 6 ma, therefore it is rejected.

This is carried on for each succeeding half of the remainder of the comparison current. The next comparison of 7.5 ma again would be rejected. The following 7.75 ma would also be rejected, etc. This would be carried on until it is completed for 11 values of reference current. Assigning a 0 to an acceptance and a 1 to rejection, the binary value of the input of 6 ma is 00111111111.

The output of the converter may be in either serial or parallel form or both. *Serial* means that the bits are a continuous train, as shown in Fig. 6-2A. In *parallel* output all the bits are applied simultaneously (Fig. 6-2B). The

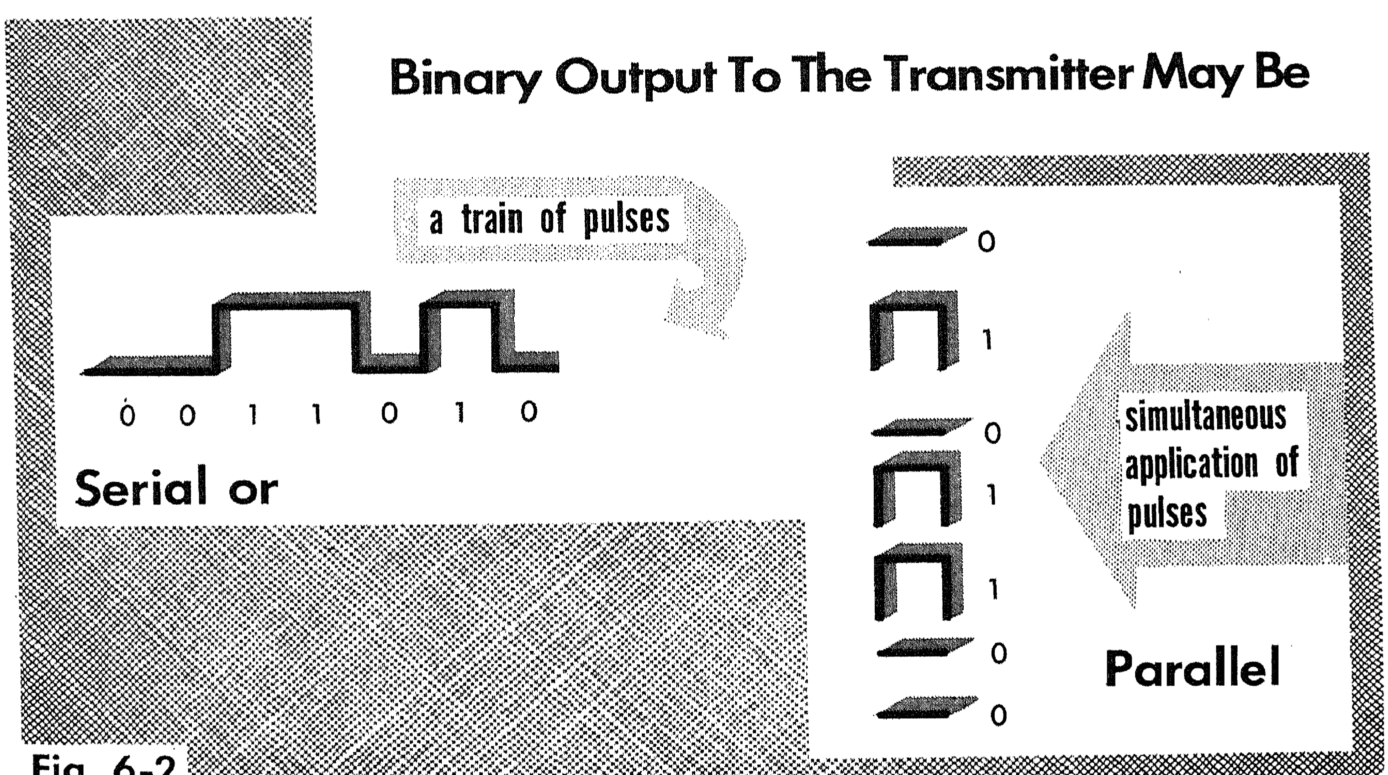


Fig. 6-2

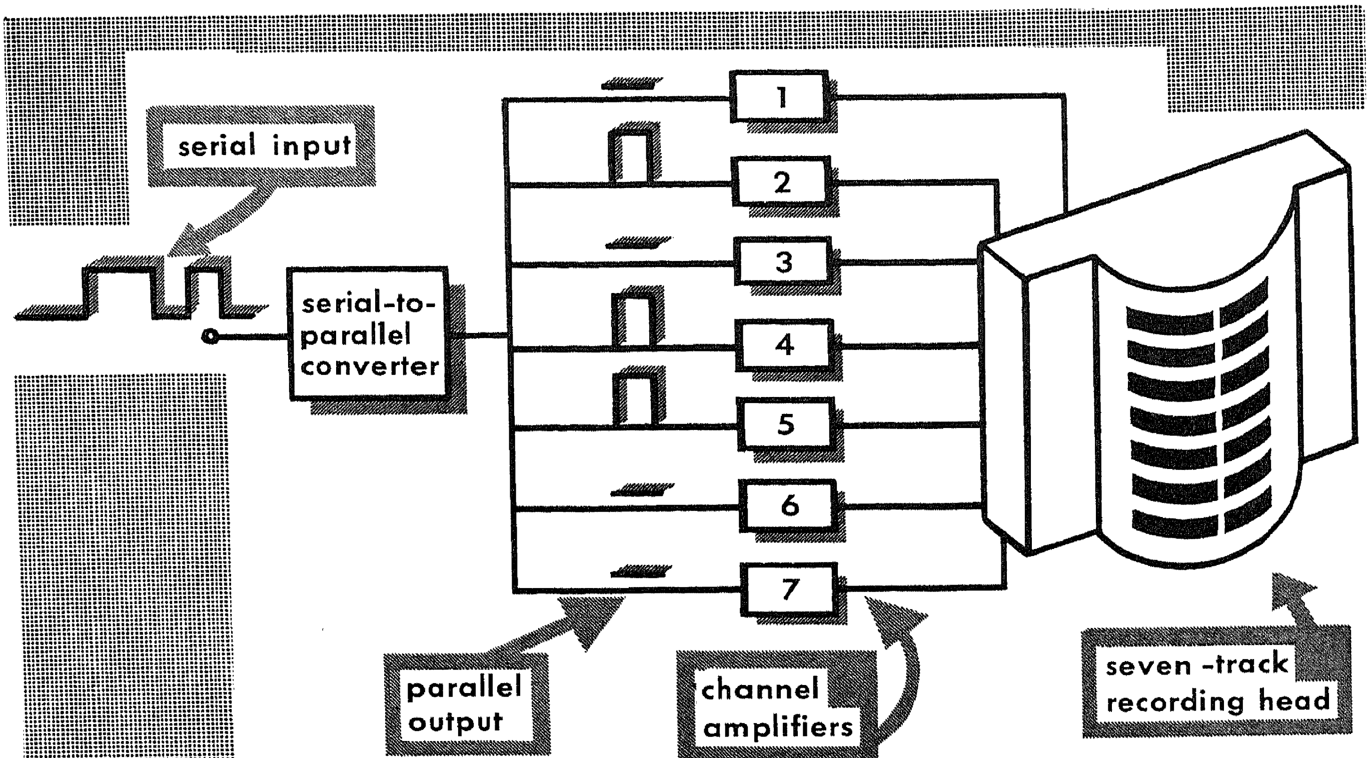


Fig. 6-3

CONVERTING SERIAL PCM TO PARALLEL PCM FOR MULTICHANNEL TAPE RECORDING

serial output is applied to an r-f transmitter where the signal is transmitted as a series of pulses that merely key the transmitter on and off. To identify the beginning of each encoded group of binary information, the beginning of each serial binary notation is indicated by turning on the transmitter for 4 microseconds at double the usual r-f transmitting power.

Another advantage of PCM is the fact that signal voltages handled in frequency- or time-multiplex systems are prone to error all along the line. The use of subcarrier oscillators, bandpass filters, discriminators, wow-and-flutter error, etc, may all add to produce a substantial error factor. In PCM, an early change of signal value to PCM removes the possibility of any change in value. The only problem is to insure readability of the signal all along the line.

PCM is the simplest type of transmission and provides a relatively noise-free signal due to its basic on-off characteristics. It is used frequently in recoverable vehicles, for aircraft testing, or telemetering at inaccessable locations, where PCM is especially worthwhile, since the output signal may be readily applied to a magnetic tape. The use of on-off-type signals simplifies the frequency response requirements of the tape recorder. For application to a tape recorder, the output signal may be in serial form on a single track or it may be in parallel form on multiple tracks.

At the receiver, it is possible to process PCM information as long as the signal level remains above the noise level. The mere recognition of the presence or absence of pulses is all that is required. The output of the receiver is a PCM signal in serial form. For use in tape recording on multiple tracks the signal is applied to a serial-to-parallel converter as shown in Fig. 6-3.

Where the PCM information is not being applied to computers, or where quick-look editing is desired, it is necessary to convert the binary-coded voltages to their original values for use with recording devices. To do this, special converters working on a principle similar to the voltage-to-binary converter will convert the binary values to their original voltage values. By the use of synchronizing circuits each voltage output can be applied to the individual channels of a multiple-channel recorder.

7. TELEMETRY DATA REDUCTION

Finding the Answers

Handling of data in a computer is analagous to the operations of a store owner who keeps complete records *(data collection)* of everything purchased and sold. At the end of a year's business, he compiles the data *(data processing)* asking these questions:

(1) How much did I sell?
(2) What percentage of the total sold was each item?
(3) Of each item, what percentage was brand X, Y, or Z?

Finding the answers is *data reduction.*

So far in our discussion of telemetry we have amassed the data in oscillograph-chart form (data collection). The next step is to break this data down to various values (data processing). Following the collection of various values, these would be plotted to show the end results (data reduction). Upon finding the end results, the engineers who worked to make the missile successful can tell to what degree they were rewarded and in what direction further effort is required.

Most often the end results of a missile test are compiled at the output of a large electronic computer. To feed the computer, the data must be prepared in the proper form. These forms take the shape of punched cards (Fig. 7-1) or magnetic tape.

Special devices have been designed specifically for converting the information contained in the charts of an oscillograph recorder to punched cards. A typical unit is operated by placing a cross-hair guide at the point of the signal trace being read. The unit automatically determines the displacement of the cross-hair from a reference line. This is converted to the correct value and then may be applied to either of two read-out devices: an electrically operated typewriter that types the values in tabular form or a special unit that punches a coded equivalent of the reading into a card for use in a computer. A typical telemetry station using this form of data reduction is shown in Fig. 7-2.

Figure 7-3 shows another form of data reduction, as used in an FM-FM system. The various outputs of the discriminators are applied to a multiplexer. The multiplexed output is then applied to a voltage-to-digital converter. This binary output is then applied to a special unit called a digital recorder that places the binary values in groups compatible with the particular computer to be used. The digital recorder, Fig. 7-4, must prepare the magnetic tape so that it records in groups similar to the information contained on a punched card. To do this, the input is placed into a memory unit. Following the insertion of the correct amount of information in the memory, the input is switched to a second memory. While the second memory is being filled, the information of the first memory is being read out in computer form to a tape recording. This is done in a relatively short period of time, to allow the first memory to be available as soon as the second memory is full. When the second memory is full, the process is

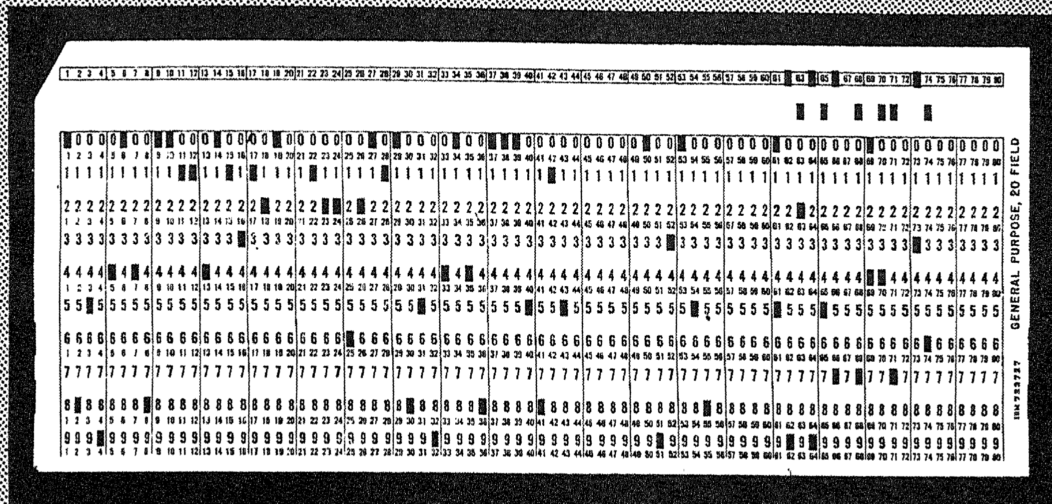
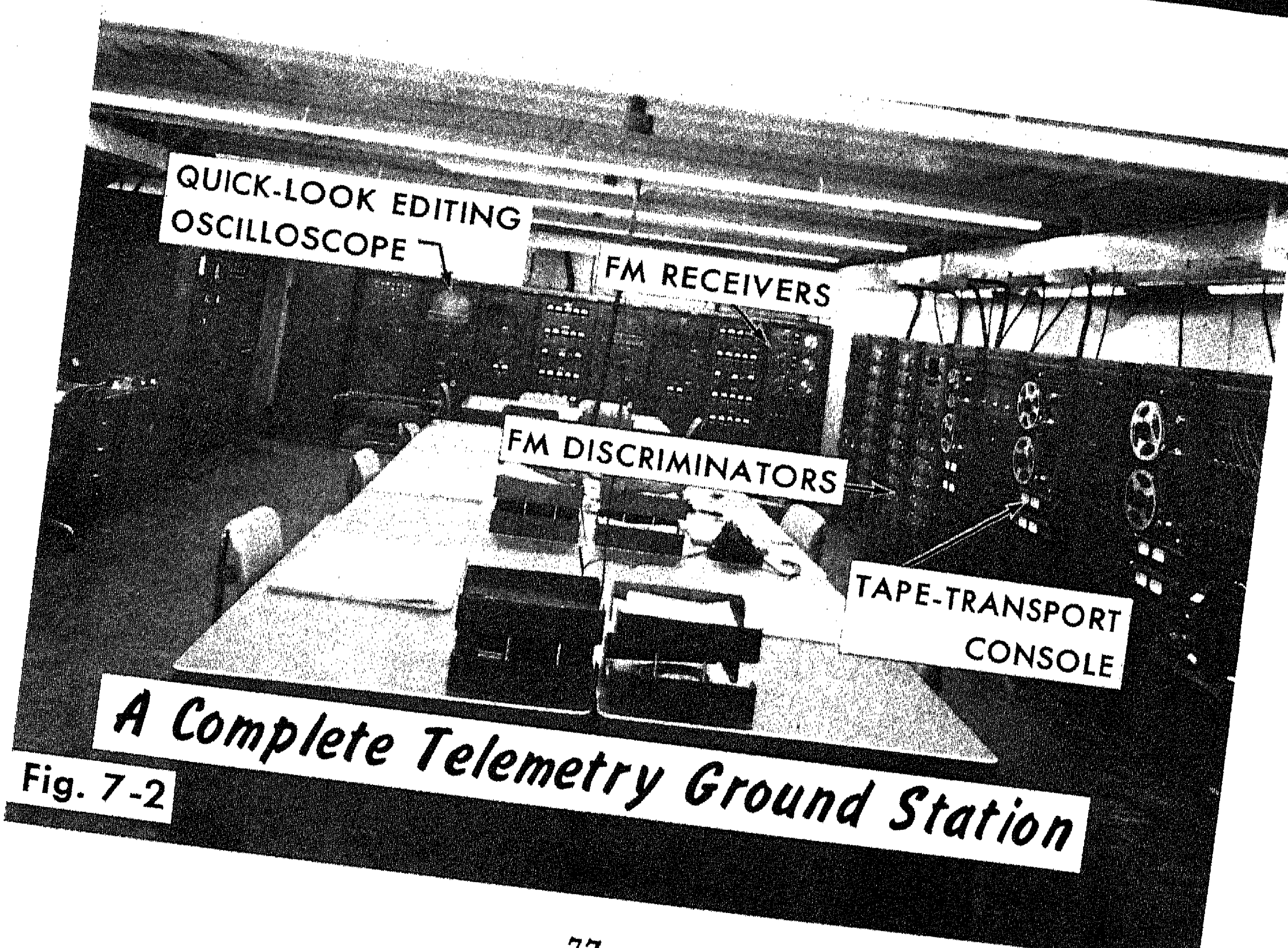


Fig. 7-1

A PUNCHED CARD CONTAINING INFORMATION TO BE FED TO A COMPUTER



A Complete Telemetry Ground Station

Fig. 7-2

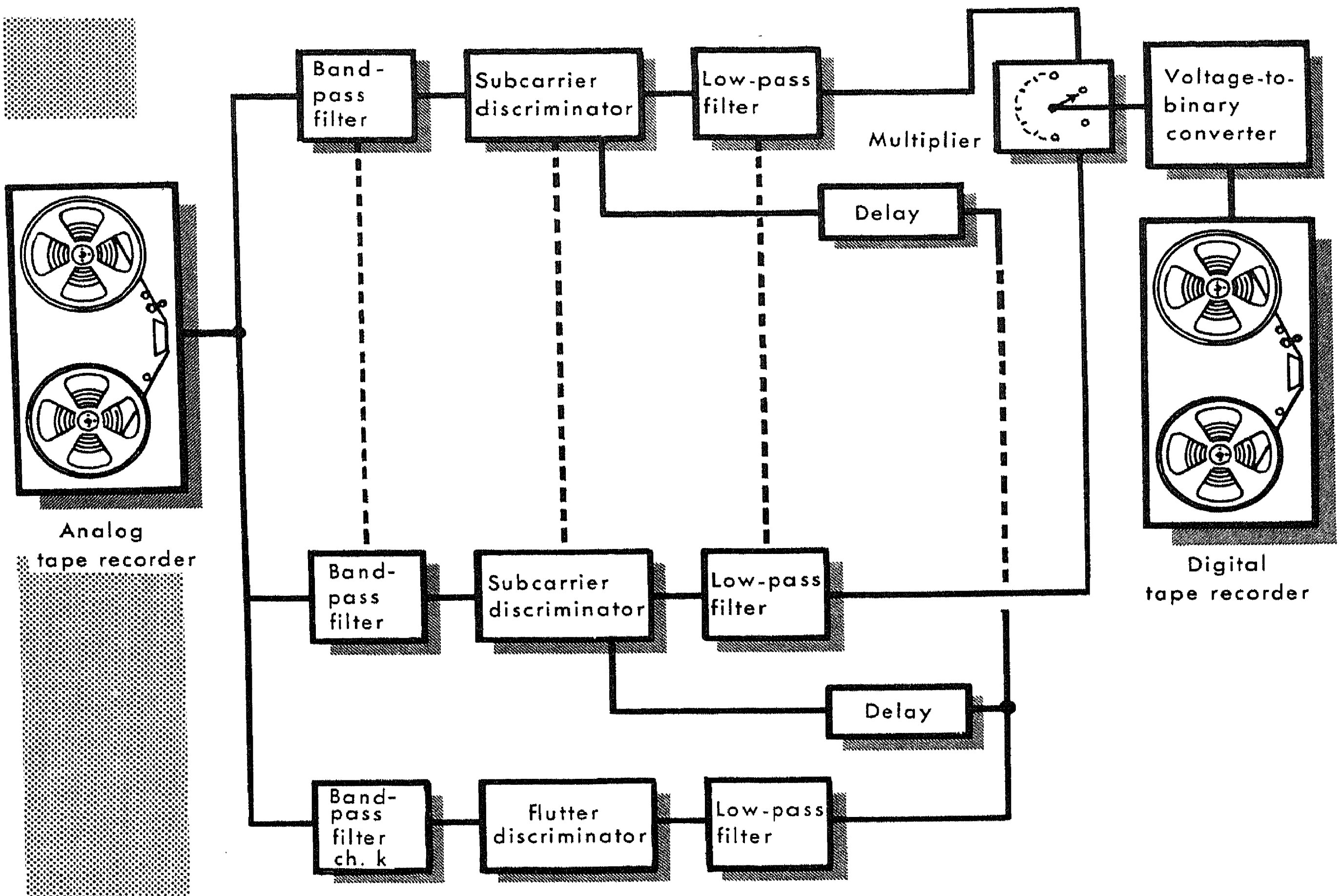


Fig. 7-3 AN FM FM DATA REDUCTION SYSTEM

ACTION OF THE DIGITAL RECORDER

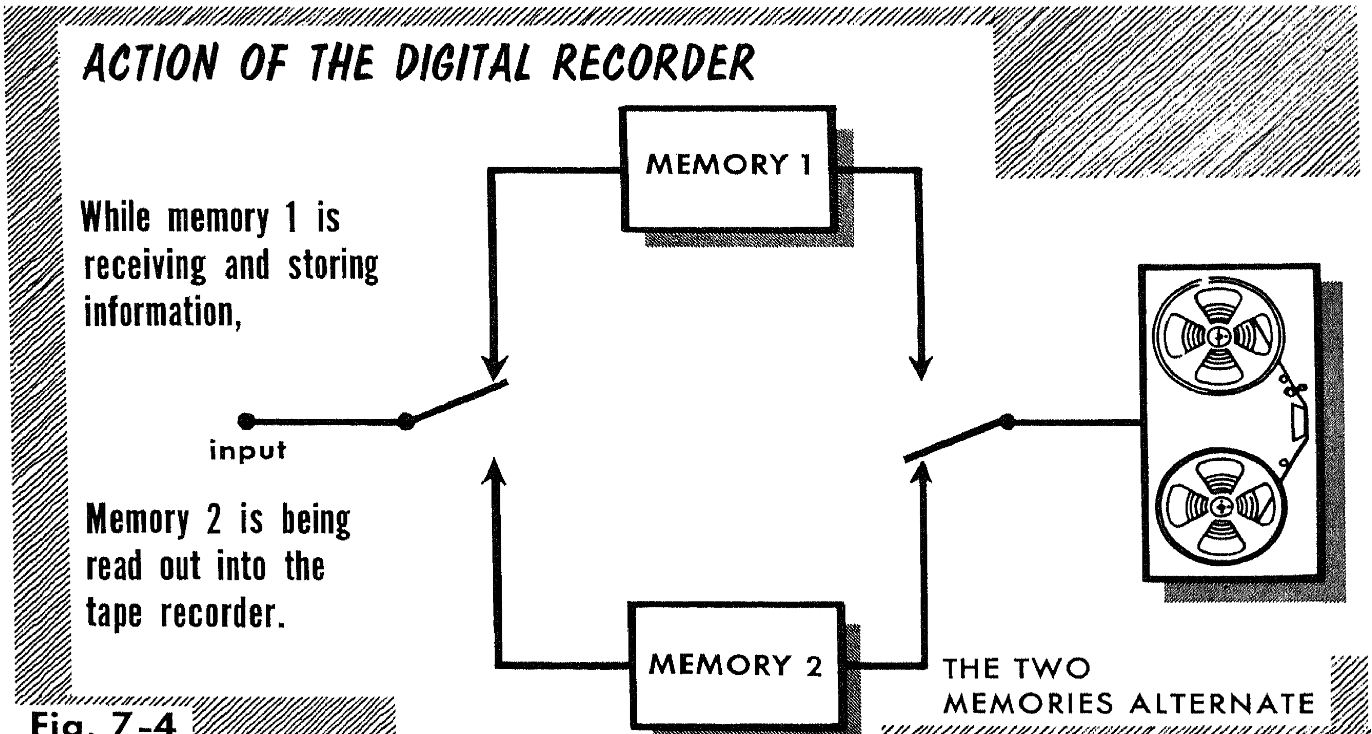


Fig. 7-4

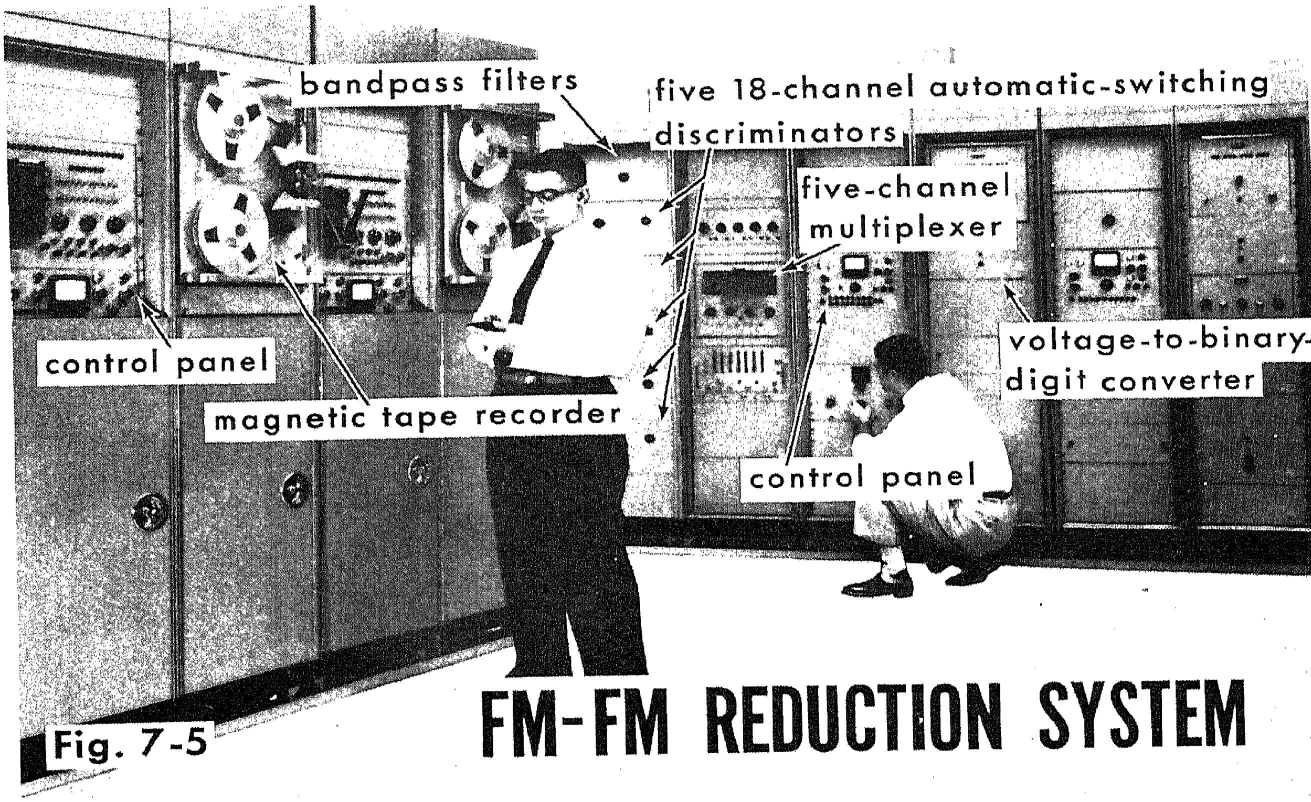


Fig. 7-5

repeated. (The input is applied to the first memory again, and the output of the second memory is read out to the tape recorder.)

A complete telemetry ground station capable of data reduction from prerecorded tapes, or directly from the incoming signal, is shown in Fig. 7-5. When used direct with an incoming signal from the receiving antenna, the outputs of the FM receivers are applied to both the tape-handling mechanism for tape recording, and to the bandpass filters and FM discriminators. The selected outputs of the discriminators are then applied to either a *hot-stylus,* or a galvanometer *light-beam*-type recorder. When the signal is from a prerecorded tape, the composite-signal output of the tape recorder is passed directly to the bandpass filters and FM discriminators and recorders. The resulting recorder charts are then applied to read-out devices. Special consoles are included for PAM or PDM signal detection and data reduction.

8. SATELLITE TELEMETRY

Satellite Telemetry Systems

Satellites involve the use of telemetry to radio to earth the information being accumulated in orbit. In addition to telemetry, optical tracking of the satellite is used to provide a wealth of information. However, telemetry is still the only way of relaying information directly from the satellite. Some of the problems encountered in construction of telemetry equipment for missile use were found to be even more severe in equipment constructed for satellite use. Every pound of satellite weight called for an enormous amount of power to place it in orbit, requiring a great degree of miniaturization. Transistors were used throughout, even in the high-frequency circuits where the ability of transistors to operate efficiently had previously

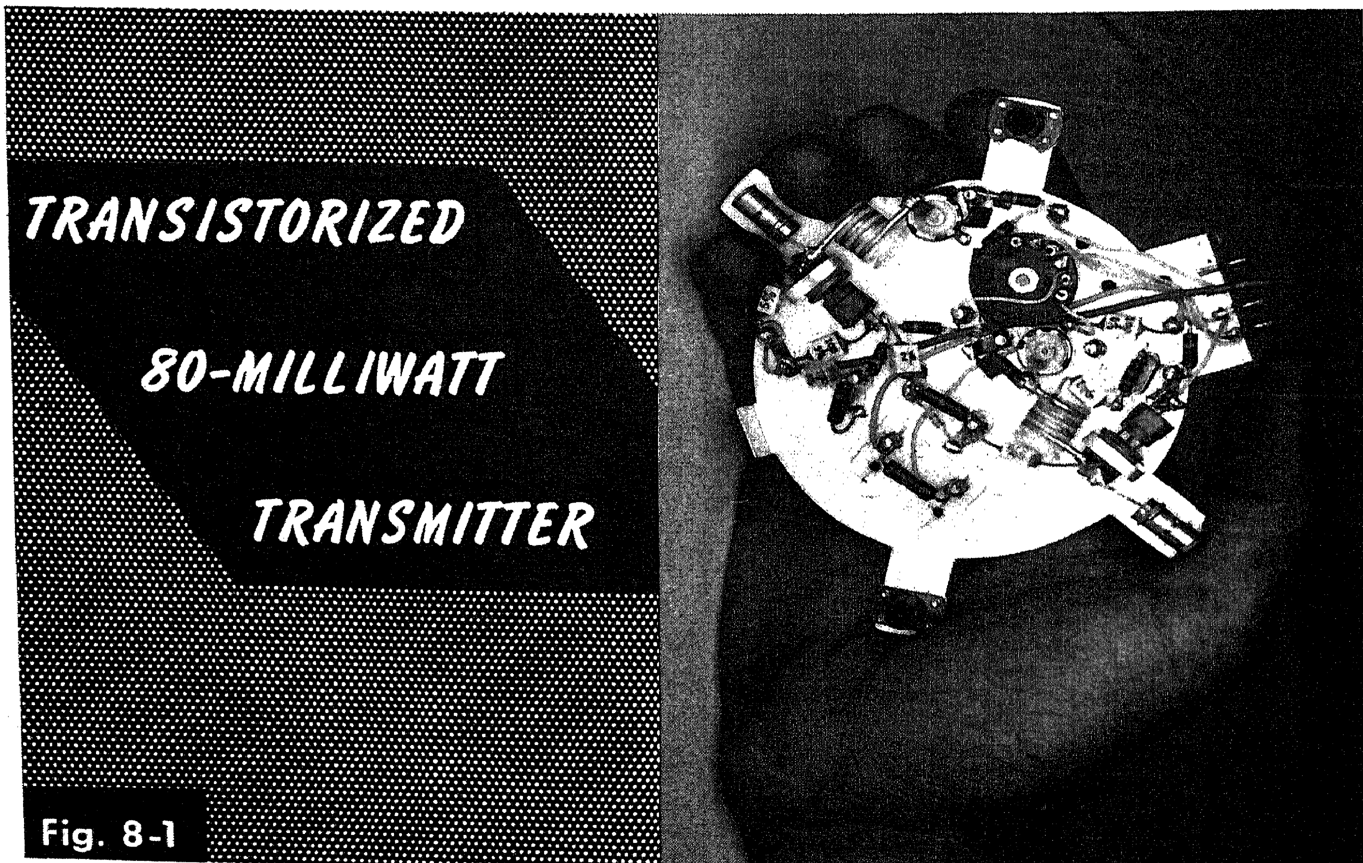


Fig. 8-1

been questioned. Figure 8-1 shows one section of a satellite telemetry system, a transmitter designed to operate at 108 mc. In addition to weight saving, the use of transistors in telemetry circuits also reduces the power requirements, permitting longer transmission and monitoring of more information-gathering equipment.

As in any telemetry system, the various transducers are used to convert physical changes to electrical variations. In satellites, the transducers are not readily recognizable as such, due to the unusual nature of the quantity or phenomena being measured. Some of the quantities measured are: solar

radiation, cosmic-ray intensity, temperatures, micrometeoric particles, cloud detection, and the earth's magnetic field.

Solar radiation measurements are taken at a particular portion of the solar spectrum called the *hydrogen Lyman-alpha region.* To obtain these measurements, a highly specialized type of ionization chamber (a gas-filled tube, that, when hit by the Lyman-alpha radiation, will cause the gas in the tube to ionize) is used. The ionization, a separation of some electrons from their atoms of gas, causes the tube to conduct.

To measure cosmic-ray intensity, a special satellite-borne Geiger-Mueller or GM tube is used. A GM tube (Fig. 8-2) is a gas-filled two-element tube,

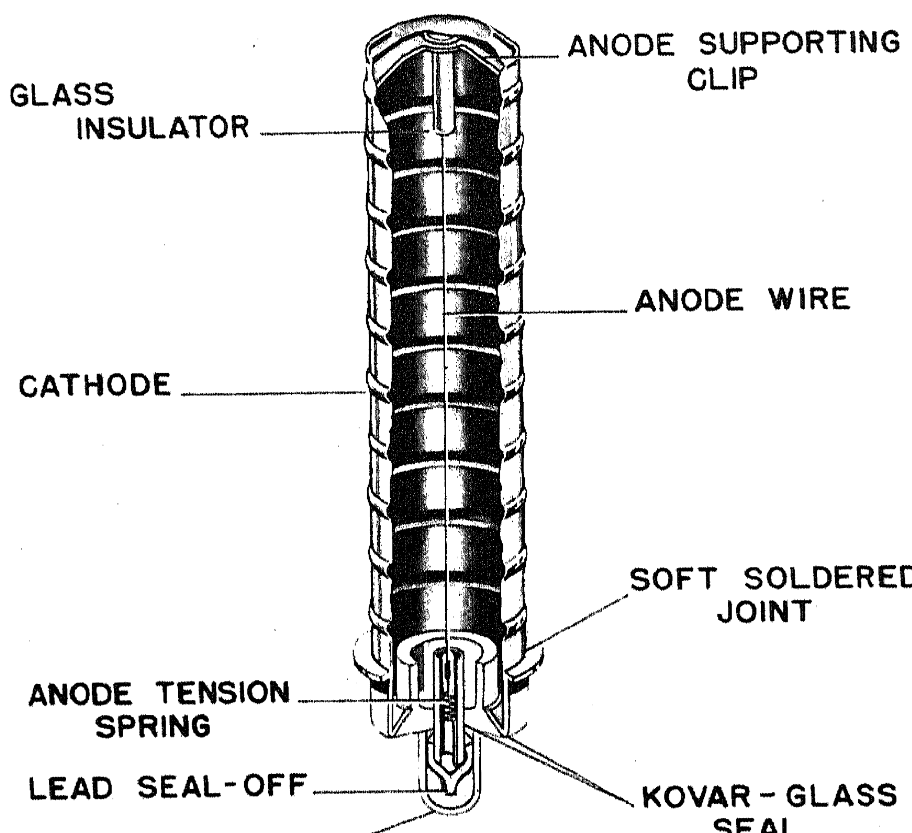
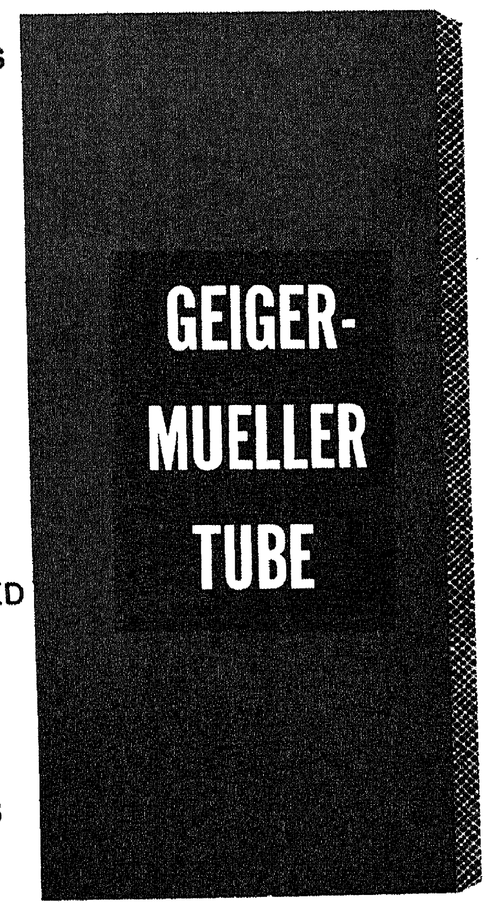


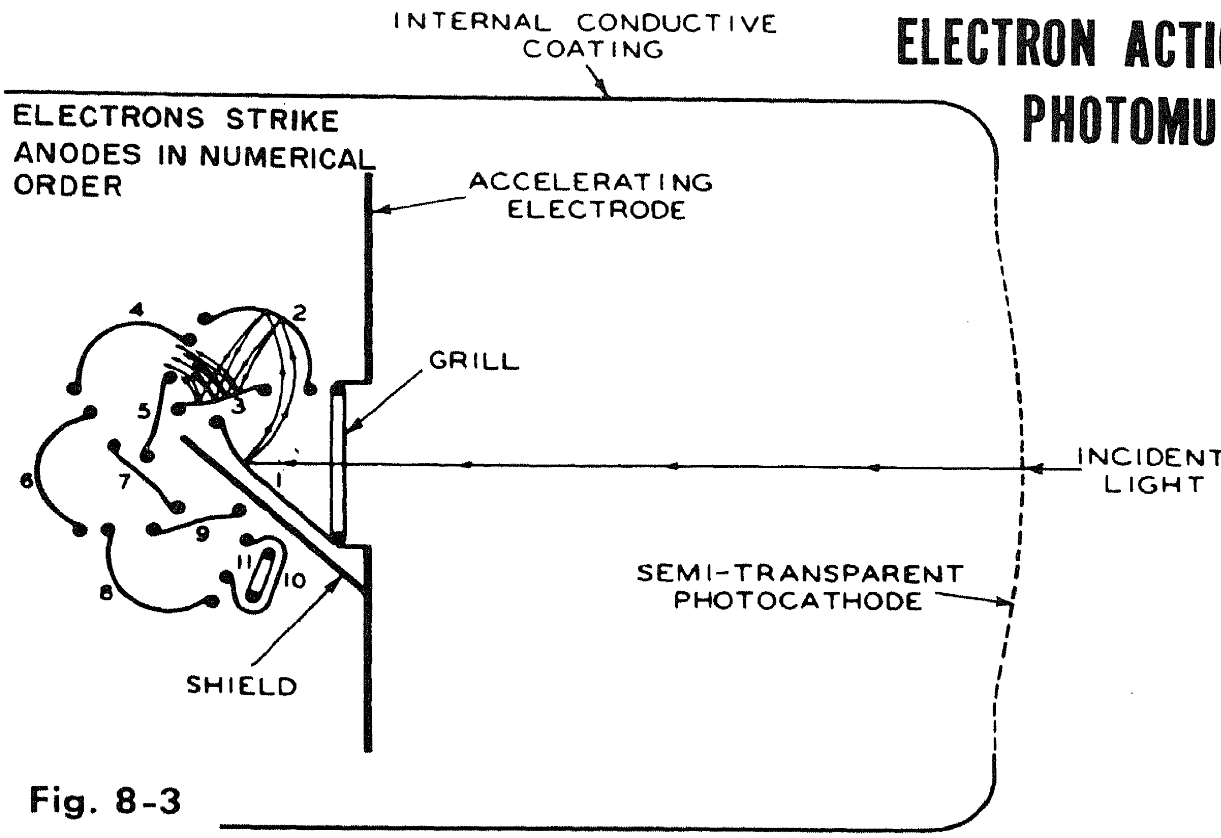
Fig. 8-2



consisting of a thin wire centered in a metal tube. A high voltage is applied to the two elements of the tube, and momentary conduction occurs when a cosmic-ray particle strikes the tube.

Scintillation counters are used to detect some types of radiation. They employ the special property of certain types of crystals that fluoresce or glow when struck by radiation particles. Different crystals are used for different types of radiation, cesium oxide being a type that glows when struck by cosmic ray particles. The glow resulting from a particle striking the crystal is so faint that it can only be detected with the aid of a

photomultiplier tube, a specially designed tube with a photosensitive cathode and numerous anodes (Fig. 8-3). The anodes are carefully placed, with each succeeding one having a slightly higher positive voltage. When the crystal glows, it causes the photosensitive cathode to emit a few electrons. These are attracted to the first anode where they cause secondary emission. The secondary electrons from the first anode are attracted to the more positive second anode where they cause an increased amount of



ELECTRON ACTION IN A PHOTOMULTIPLIER TUBE

Fig. 8-3

secondary emission. This process is repeated for ten or more anodes. The output of the final anode will be a pulse of sufficient amplitude to operate various associated circuits.

To measure temperature, thermistors are used. A thermistor, Fig. 8-4, as previously explained is a nonlinear resistor whose resistance value changes with changes in temperature.

To indicate collisions between the satellite and micrometeoric particles, different types of special gages, called erosion gages, have been devised. One type of erosion gage consists of a thin film-resistor deposited on glass. Collisions with micrometeorite particles wear away the resistance film, changing the value of resistance. Another technique uses a group of sensitive microphones attached to the skin of the satellite. As these microphones are struck by the micrometeoric particles, the signals are counted by special circuits. The use of a photosensitive element, such as a cadmium sulfide cell, is another method. Sunlight striking the cadmium cell provides an

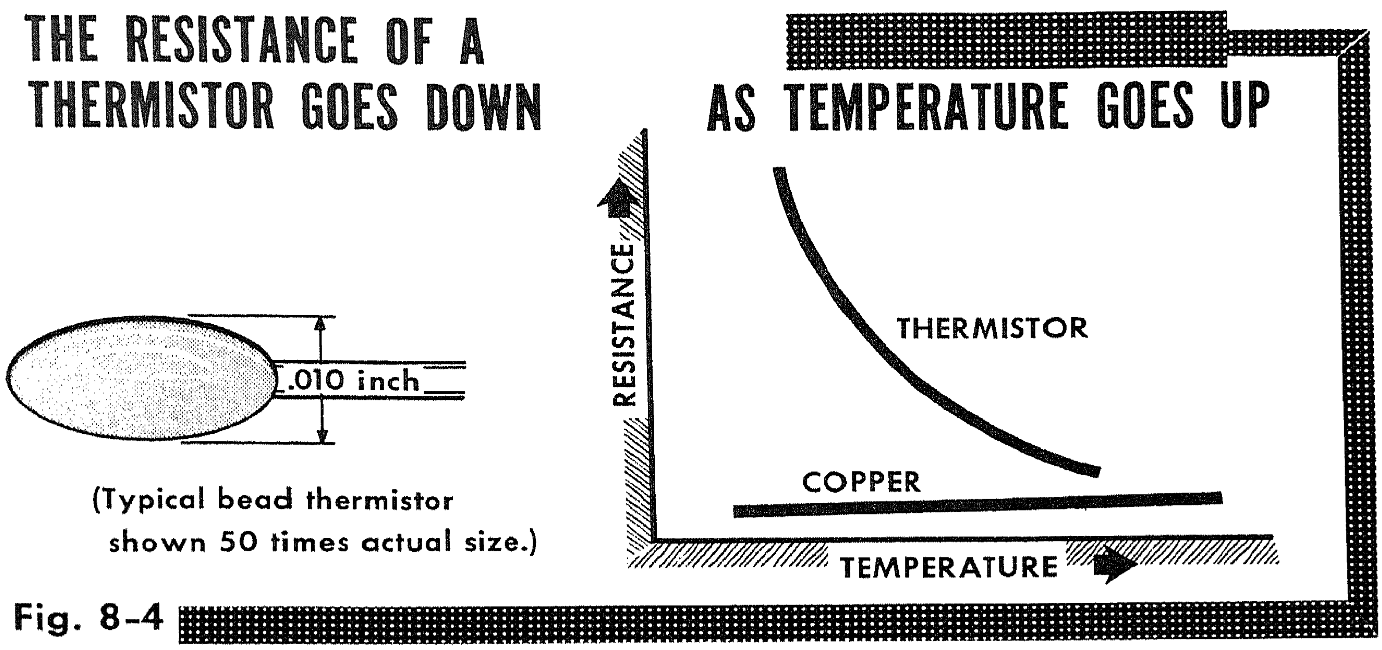


Fig. 8-4

output signal commensurate with the area of the cell exposed. To measure erosion by collision with micrometeorite particles, the cell is covered by a thin opaque material blocking the light. As the cell is struck by micrometeorite particles, the opaque covering is removed, permitting increased light output from the cell. Another erosion gage consists of a square block of resistance wires shaped like a grid. When a micrometeorite hits and breaks one of the wires, the total resistance of the grid changes.

To indicate impact with particles sufficiently large to penetrate the outer skin, the inside of the satellite is divided into two zones with different values of pressure. By fixing the pressure in the two zones at slightly different values, it is possible for a single differential-pressure measurement to indicate a puncture of either or both zones.

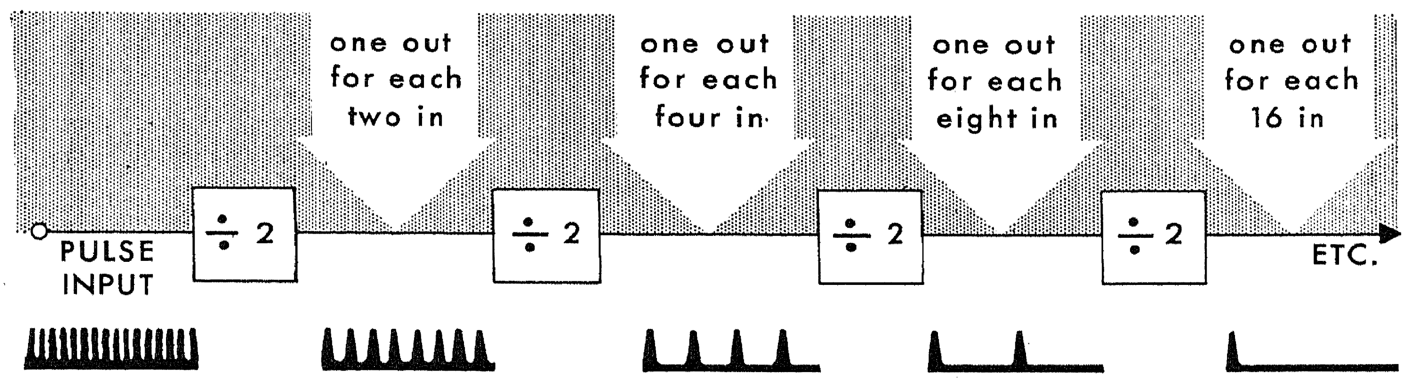
To determine the area of earth covered by clouds, a three-inch mirror focuses and reflects the light of the clouds to a miniature infrared detector. To distinguish between day and night, silicon solar cells are used to turn the equipment off when the satellite is on the dark side of the earth.

To measure the intensity of the earth's magnetic field, a magnetometer is used. The magnetometer consists basically of a coil of wire, a bottle of water, and a power supply. The coil is wound about the bottle of water. When switched to the power supply, the coil applies a strong magnetic field to the water. This field polarizes protons in the water in the direction of the applied field. The power supply is then turned off, removing the magnetic field, and the coil is connected to an amplifier. Upon being released by the magnetic field, the polarized magnetic protons in the water start to spin about their original position and induce a signal in the coil. The frequency of the induced signal varies depending upon the strength of the magnetic field of the earth. (Typical variations are from 800 to 2200 cycles.)

subcarrier oscillators used with satellites operate on the same RDB standard frequencies used in missile telemetry. These most often will be the lower-frequency Channels 2 through 5.

To measure some quantities, such as the number of micrometeorite particles striking the microphones, special circuits called *counters* are used. These circuits operate with binary techniques, as discussed in a previous chapter. Assuming a 2-tube circuit, the first signal impulse causes tube A to conduct; the second signal impulse causes tube A to stop conducting, and automatically causes tube B to conduct. The third signal impulse again causes tube A to conduct, while at the same time it causes tube B to stop conducting, and provides an output pulse. Reviewing the operation, we find that for every 2 pulses applied to tube A, there is 1 output pulse from tube B. Since this is dividing by 2, we can call it binary division.

Following it a step further, using an additional 2-tube circuit and applying the output of tube B to the additional unit, we find that we can then divide



The Use Of BINARY DIVISION Or 'COUNT-DOWN'
Fig. 8-5

by 4. Adding still another binary count-down circuit, we require 8 signal impulses to tube A to have 1 output pulse. (See Fig. 8-5.)

In a typical satellite, a commutating switch and/or coder as well as count-down circuits is used between the output of the various measurement devices and the input of the subcarrier oscillators. The commutating switch at the output of the measuring devices has four inputs yielding four samples per frame, with a frame rate of six per second, providing a commutation rate of 24 samples per second. This output is applied to a coder converting it to a PDM signal with time durations varying from 4 to 30 milliseconds.

The outputs of the subcarrier oscillators are applied to either of two transmitters. One transmitter has an operating frequency of 108 mc with a power output of 10 milliwatts. This transmitter is designed to operate for approximately two weeks and is used for radio tracking. It telemeters information by being phase-modulated by four subcarrier oscillators. In

addition, a higher-power transmitter operating at 108.03 mc may be set to operate upon receipt of a special interrogating signal. To operate the higher-power transmitter only during times when it is passing over receiving stations, a special receiver is built within the satellite using the continuously operating 108-mc transmitter as a local oscillator. Upon receiving the interrogating signal, a time-locking relay turns the 108.03-mc transmitter on for a period of approximately 30 seconds.

This system is also useful for those satellites that contain a tape recorder. As the satellite spins in its orbit, the information it obtains is placed in a specially designed miniature tape recorder. When passing over a receiving station, the interrogation signal operates the tape recorder, causing it to play back over the higher-powered transmitter. By having the transmitter operate for only short periods of time, the life of the batteries is extended.

The two types of antenna used for the transmitters of the satellite are a dipole and a turnstile. The turnstile antenna consists of four equal lengths of wire that radiate from the sphere or rocket in a form similar to the spokes on a wheel. The spherical satellite globe is electrically divided into two halves to create a dipole. In the rocket type of satellite, the nose cone is electrically separated from the rocket shell. Most often, the dipole antenna is used to radiate the 108-mc signal and the turnstile antenna the 108.03-mc

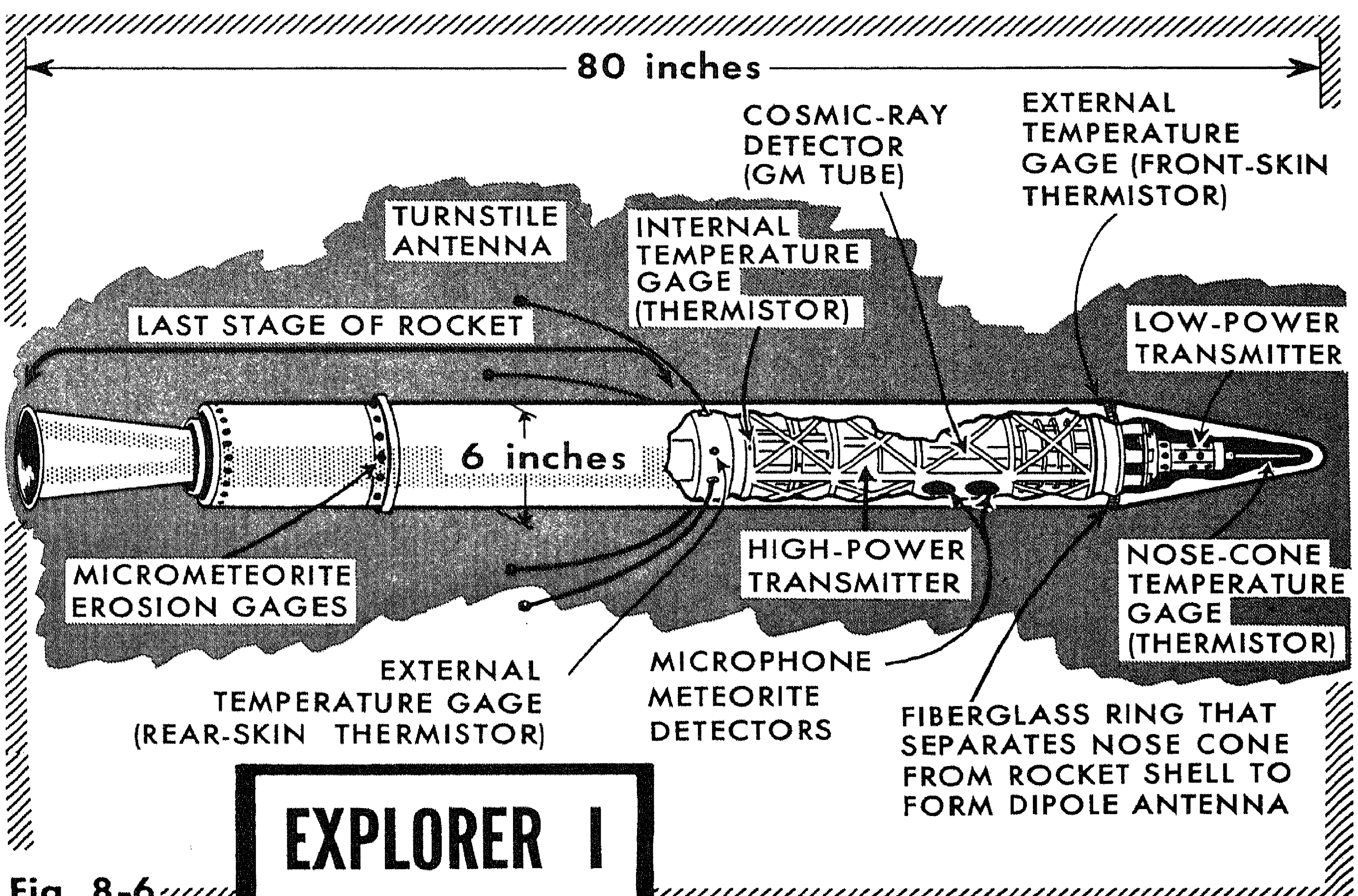


Fig. 8-6

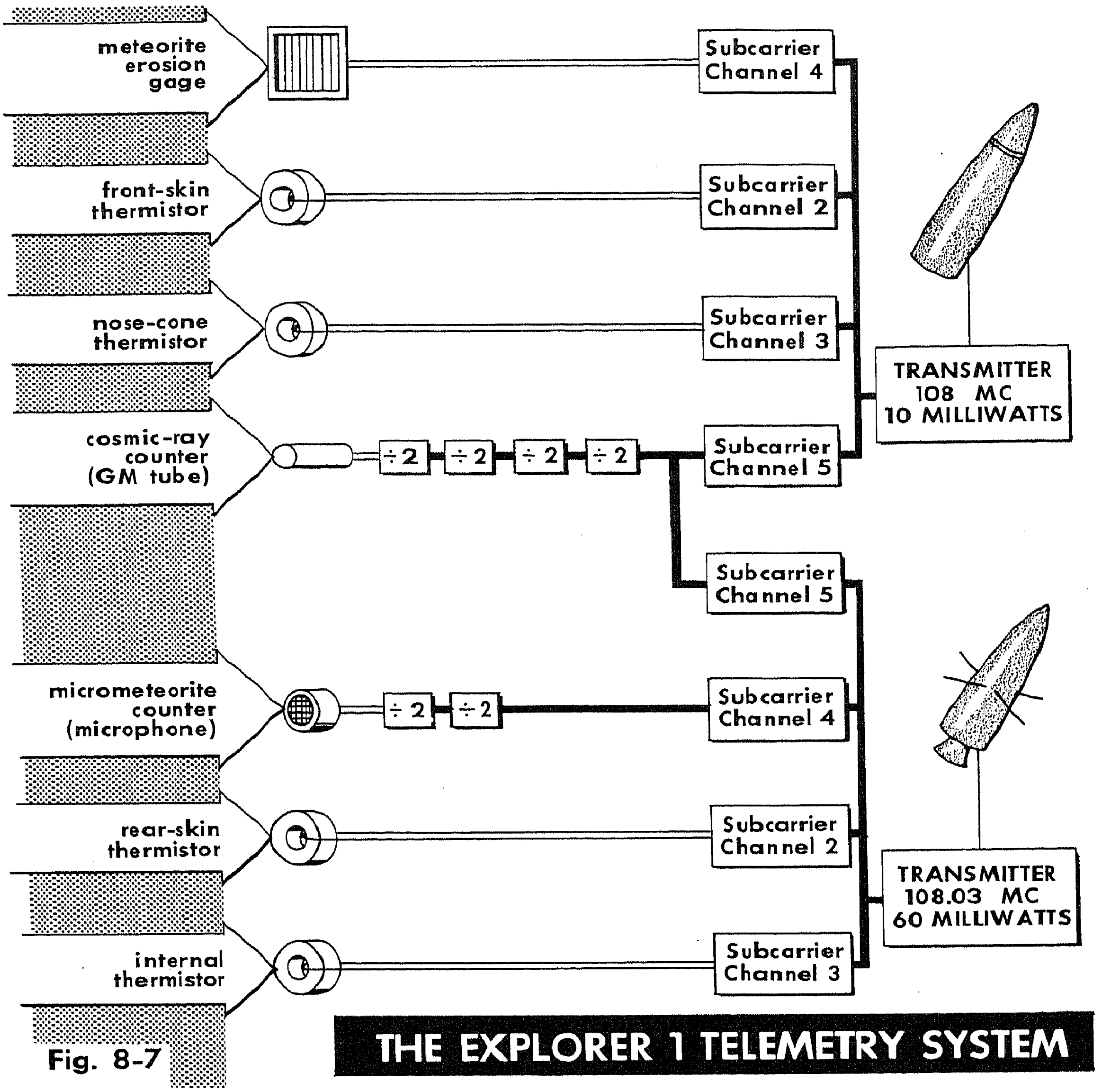


Fig. 8-7 THE EXPLORER 1 TELEMETRY SYSTEM

signal. As mentioned previously, any or all of the different measuring devices may be applied in many combinations to form one satellite system. The future will see many of these combinations in different Vanguard or Explorer satellites. The telemetry system of the satellite Explorer I is a typical example. Figure 8-6 shows the construction of the satellite and placement of some of the indicating equipment. Figure 8-7 is the block diagram of its telemetry system.

Located on the front skin of the satellite is a thermistor whose resistance determines the output frequency of a Channel-2 subcarrier oscillator.

Another thermistor placed on the nose cone determines the output frequency of the Channel-3 subcarrier oscillator. Situated in a circle about the satellite, near the tail end, are 11 micrometeorite grid-type erosion gages, all wired in parallel. As the resistance wires are struck and broken by the micrometeorites, the total resistance of the gages increases, changing the output frequency of the Channel-4 subcarrier oscillator. Centered in the satellite is the GM tube used to detect cosmic rays. The output of the GM tube is applied to a binary counter. After receiving 16 counts, the Channel-5 subcarrier oscillator is switched to another output frequency. After receiving another 16 counts, the subcarrier oscillator is switched back to its original output frequency. The outputs of the four subcarrier oscillators are applied to phase-modulate the 10-milliwatt 108-mc transmitter. The antenna is a dipole using the nose cone and rocket shell for the two dipole elements.

In addition to using the output of the GM tube to control the Channel-5 subcarrier oscillator in the lower-powered transmitter, it is also used to control a Channel-5 subcarrier oscillator in the higher-powered system. In addition, a thermistor placed on the rear skin of the satellite determines the output frequency of a Channel-2 subcarrier oscillator.

In a central position within the heart of the telemetry package is another thermistor used to measure the internal temperature. This thermistor controls a Channel-3 subcarrier oscillator. Mounted on the outer skin of the satellite is a sensitive microphone, whose output, when struck by a micrometeorite, is applied to a binary counter. After four counts have been received, an output pulse is applied to the Channel-4 subcarrier oscillator causing it to shift frequency for a moment, and then return to its original frequency. The outputs of the four subcarrier oscillators are applied to a 60-milliwatt 108.03-mc transmitter. The signal is radiated by the turnstile type of antenna.

Vanguard I

Following Explorer I, Vanguard I was placed aloft. A small sphere, it contains 6 clusters of solar cells distributed over its surface, so that at least one will always be facing the sun. The satellite contains two transmitters, one operating from batteries and another from the energy created by the solar cells. The transmitter operating from batteries functioned for two weeks; the transmitter operated from the solar cells was still transmitting 9 months later. The ultimate life of the solar cells and transmitter is undetermined. The measurements taken by Vanguard I are those of the internal and external temperature of the satellite.

Explorer III

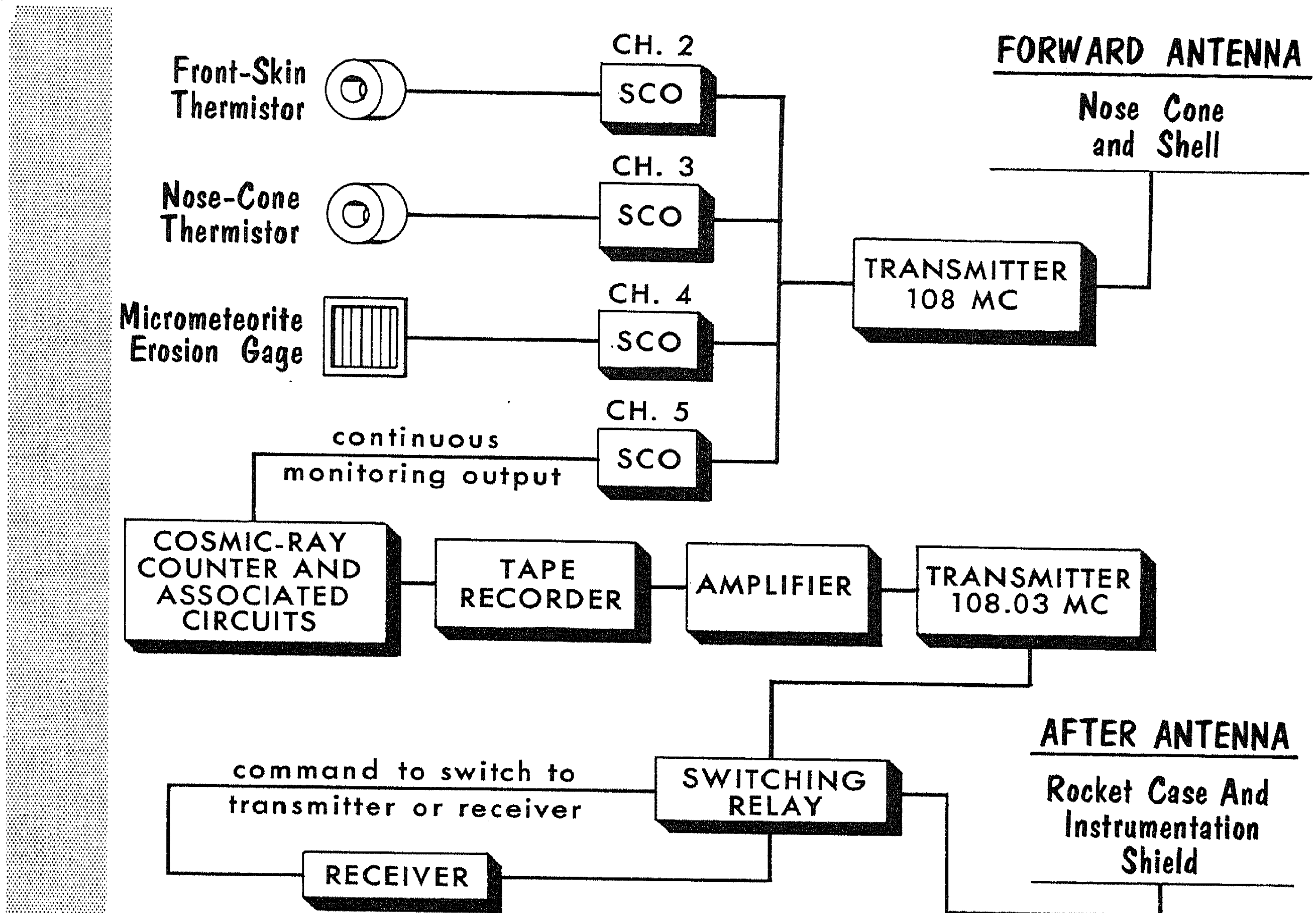
Explorer III was the next U.S. satellite to orbit. A portion of Explorer III instrumentation is similar to that used in Explorer I; however, it has a radio

receiver, which when it picks up an interrogated signal as it passes over a ground receiving station, operates a tape recorder mechanism to reproduce as much as two hours of recorded information. The tape recorder used is of special design, and is only two and one half inches in diameter, approximately the same height and weighs about one half pound. The tape recorder operates at .005 inch per second while recording, permitting 2 hours, or the equivalent of 30,000 miles of observations to be placed on the tape. The tape recorder at playback is read off at high speed, taking from 5 to 7 seconds to play back all the recorded information.

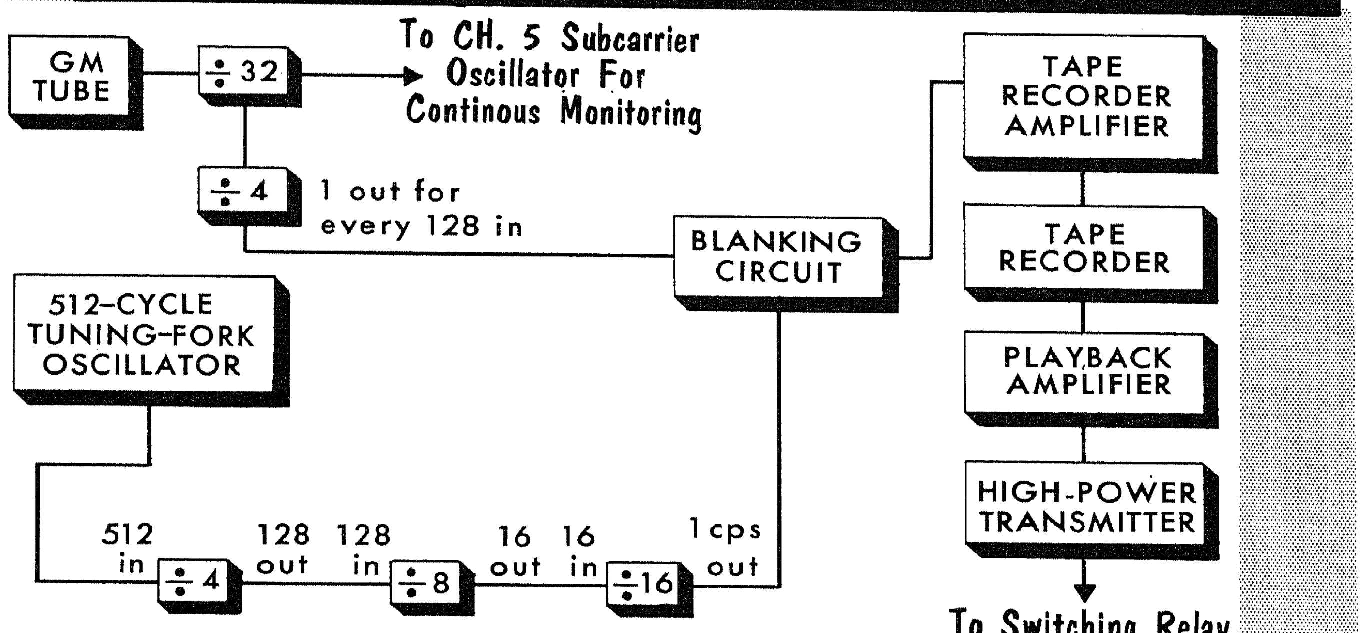
The turnstile antenna used in the previous satellites was believed to cause twisting about the longitudinal axis, causing a deterioration in the quality of the transmission. The two antennas of Explorer III are integral parts of the satellite. The low-power 108-mc transmitter uses the nose cone and shell as a dipole antenna. The high-power 108.03-mc transmitter uses the last stage rocket motor case and the shell containing the satellite instrumentation. (The same antenna that is used for the high-power transmitter is also used for the radio receiver.)

A block diagram of the Explorer III telemetry package is shown in Fig. 8-8. The low-power transmitter operating at 108-mc continuously monitors the same information as the Explorer I. The high-power transmitter operating at 108.03 mc operates alternately with the command receiver when it picks up an interrogating signal from the ground station. The command signal causes the receiver to trip special latching relays that cause the receiving antenna to be switched to the high-power transmitter. The tape recorder then rapidly reads out its information. The relay is then released, and the receiver is switched back to the antenna. The tape recorder again starts to record the output of the cosmic ray counter.

In the detailed block diagram of the cosmic ray counter circuitry, incident cosmic rays striking the GM tube provide output pulses. These pulses are applied to binary circuits that divide the number of input pulses to provide one output pulse for each 32 input pulses. Two outputs are obtained, one of which is applied directly to the Channel-5 subcarrier oscillator of the low-powered continuous-monitoring circuits. The other output is applied to another divide-by-4 binary circuit, to provide one output pulse for each 128 pulses from the GM tube. This output is applied to a blanking circuit. A special tuning-fork oscillator is operated at 512 cycles, the output of which is applied to binary circuits to provide a 1-cps output that is also applied to the blanking circuit. The output of the tuning-fork oscillator is continuously recorded on the slowly moving magnetic tape. When 128 pulses have been received by the GM tube, the resulting output pulse from the divide-by-4 binary circuit applied to the blanking circuit will blank the next tuning-fork-oscillator pulse. The result is a lack of a one-cycle-per-second pulse indicating on the magnetic tape that an additional 128 counts has been reached since the last blanked-out pulse.



Block Diagram of EXPLORER III SYSTEM



The COSMIC-RAY COUNTER and its ASSOCIATED CIRCUITS

Fig. 8-8

When the receiver is interrogated and the tape is operated at playback, the speed of the tape recorder is approximately 1000 times faster, producing approximately a 1-kc square wave with gaps indicating counts of 128 pulses.

Explorer IV

The radiation encountered by satellites Explorer I and III was sufficiently intense to jam the counters used. Explorer IV was designed solely to measure this intense radiation. The satellite contains four cosmic-ray radiation detectors. Two of the detectors use GM tubes and two use scintillation counters, with associated binary divider circuits referred to as "scalers." The two GM counters are used to measure the radiation inside the satellite. One of the GM tubes is covered with a 1/16-inch lead shield to measure the amount of radiation that would penetrate a protective coating.

The two scintillation counters are used to measure the external bombardment of radiation. One is used to measure the total energy of the particles and the other to measure the total number of particles striking it. The output of the scintillation counter used to measure the total number of particles is applied through scaler circuits to modulate one subcarrier channel. When the radiation is excessively high, additional scaler circuits will further divide the high number of output pulses and apply the stepped-down reading to another subcarrier oscillator.

The complete satellite (shown in a cutaway view in Fig. 8-9) contains four radiation counters and associated scalers, which modulate five subcarrier

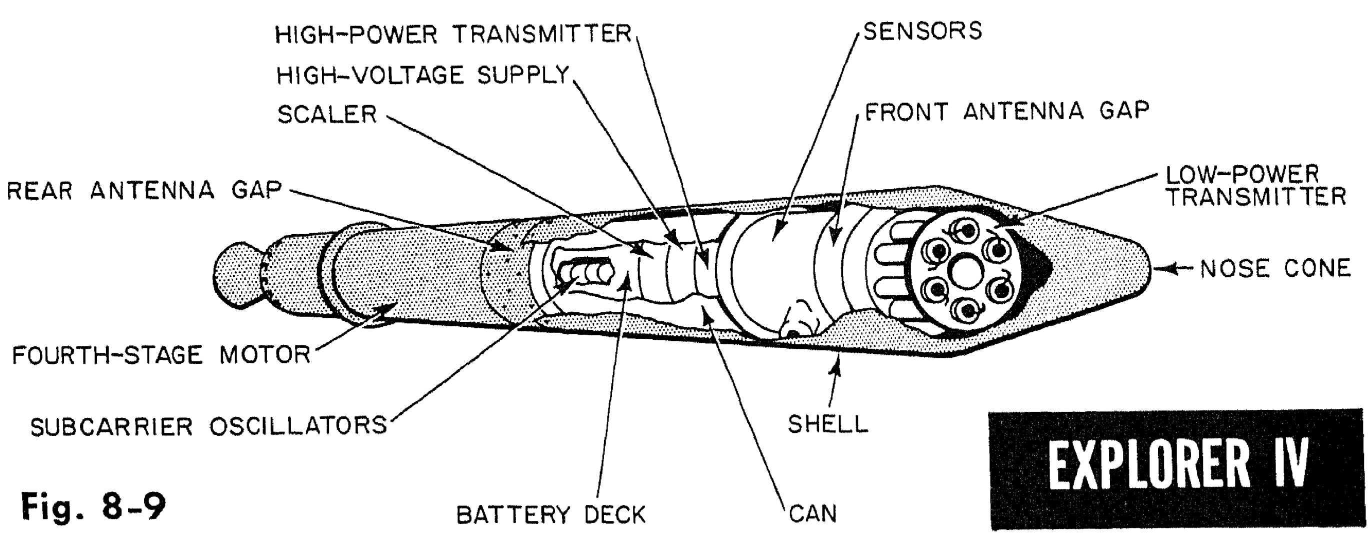


Fig. 8-9

oscillators. The output is transmitted continuously on both 10-milliwatt and 30-milliwatt transmitters. As in Explorer III, the antennas are an integral part of the satellite.

Pioneer I

Pioneer I is the Lunar Probe sent aloft by the Air Force. The entire vehicle on its launch pad just prior to firing time is shown in Fig. 8-10. The telemetry package used was a highly sophisticated unit designed to accomplish

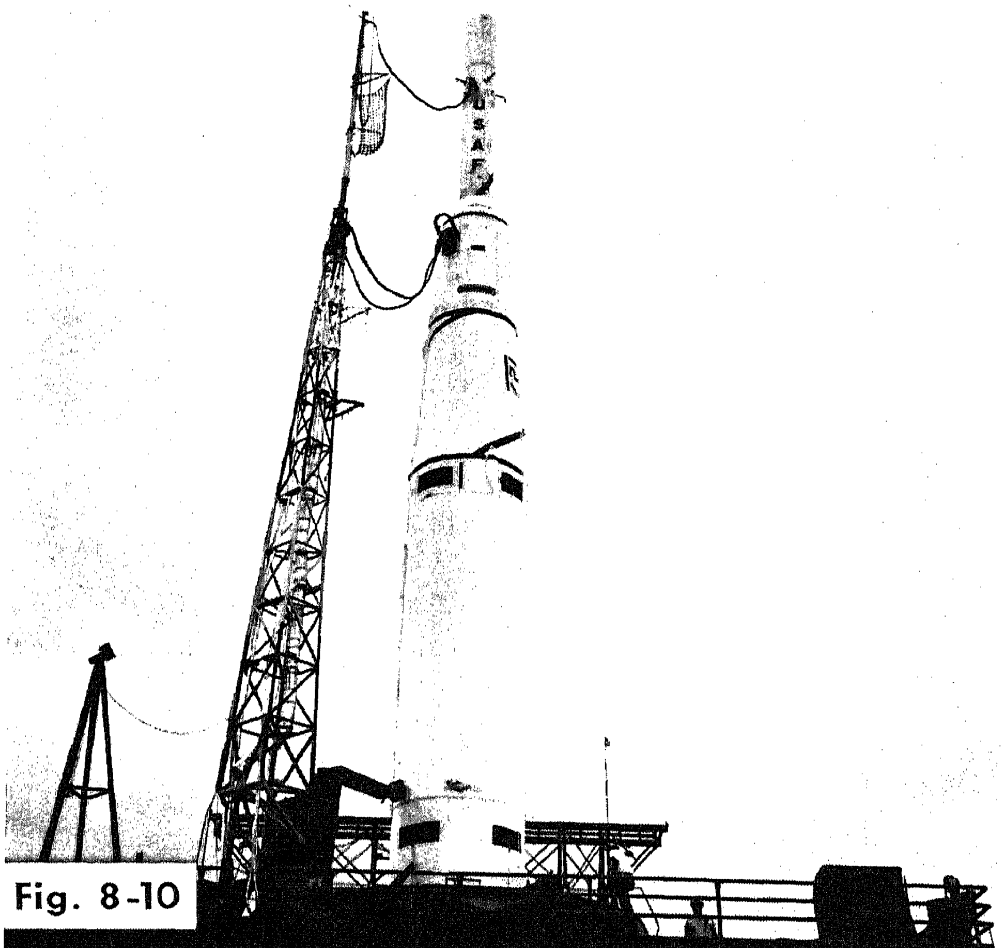


Fig. 8-10

LUNAR PROBE VEHICLE

many things. The equipment (Fig. 8-11) included a magnetometer to measure the intensity of the magnetic field both of the earth and of the moon. It also contained a micrometeorite impact recorder and thermistors to measure the internal temperature of the unit. An ion chamber was included to measure radiation. A novel feature was the inclusion of a special infrared television device to scan the hidden surface of the moon. A command receiver was incorporated to separate the third-stage rocket from the payload containing the telemetry package, and to fire the retro-rocket and the small vernier rockets.

Satellite Receiving Antennas

The antenna for satellite receiving stations is usually placed in a fixed position and is part of the radio-tracking system. Tracking the satellite is done by an electrical version of triangulation, requiring from two to as

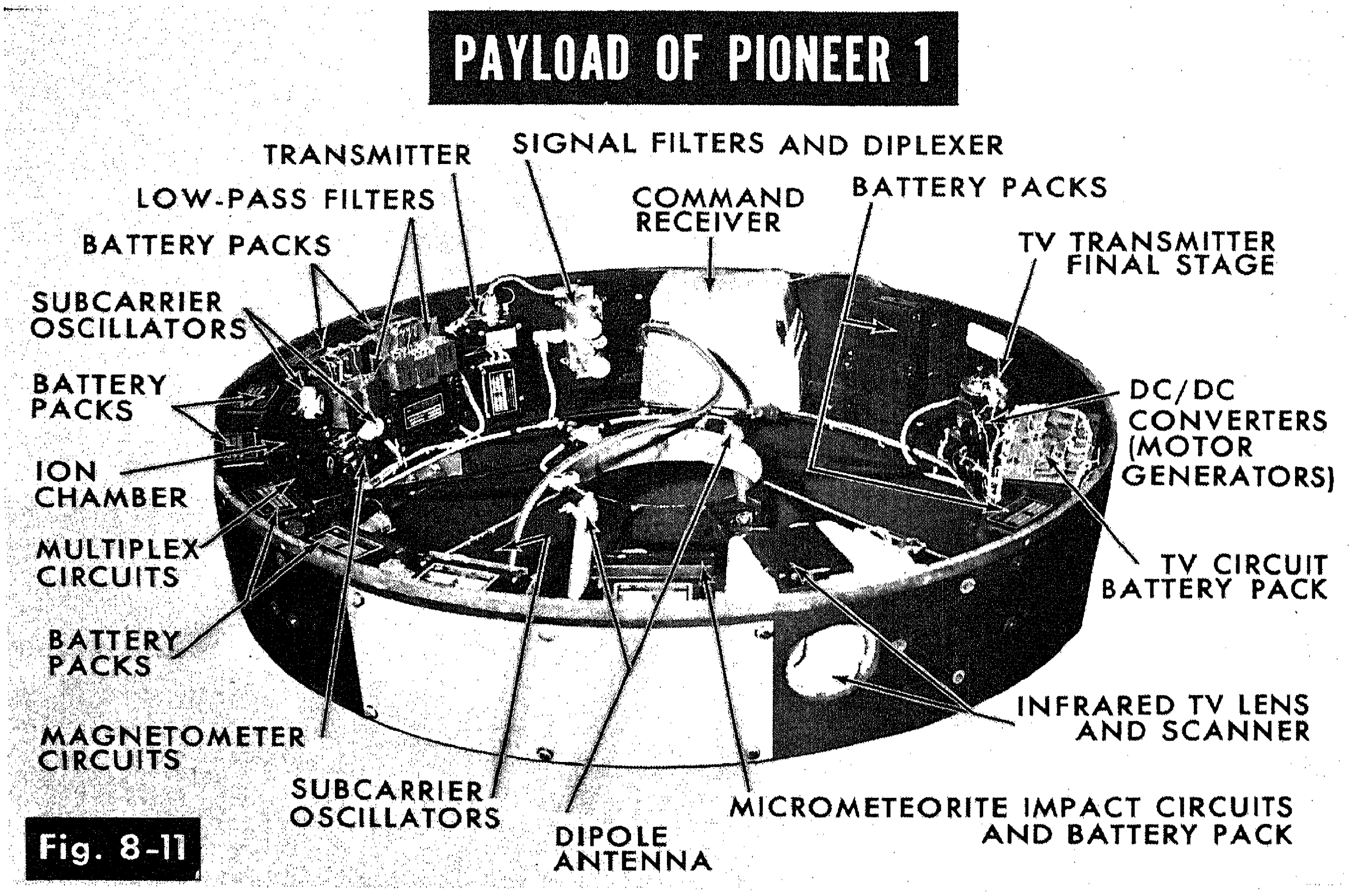


Fig. 8-11

many as eight antennas. The type of antenna used is usually a multiple array of specially interconnected antennas of Yagi design and construction (Fig. 8-12).

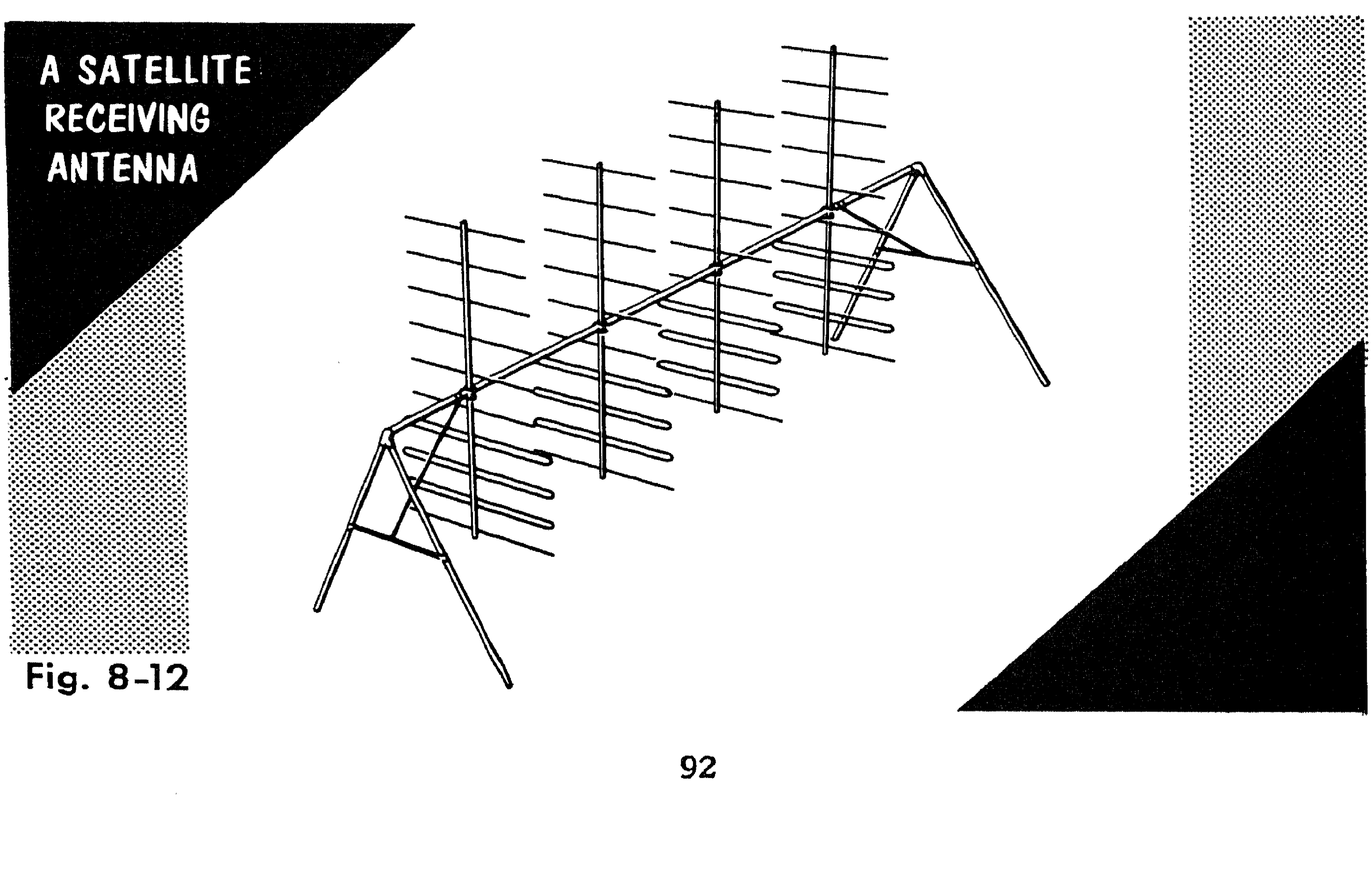


Fig. 8-12

The receiver can be a portion of the tracking system or it can be a separate receiver used specifically for telemetry. The detected output is placed on a magnetic tape and forwarded to the various centers such as the Naval Research Laboratory, the Jet Propulsion Laboratories, Cambridge Air Force Research Center, etc. depending upon the nature of the information contained on the tape. At these centers, the data is processed in the same manner used for missile telemetry.

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TELEMETRY STANDARDS FOR GUIDED MISSILES*

(IRIG Document No. 103-56)

Prepared by Inter-Range Telemetry Working Group
Inter-Range Instrumentation Group
Air Force Missile Test Center
Holloman Air Development Center
Naval Air Missile Test Center
Naval Ordnance Missile Test Facility
Naval Ordnance Test Station
White Sands Proving Ground

FOREWORD

A standard in the field of telemetry for guided missiles was established in 1948, by the Committee on Guided Missiles of the Research and Development Board (RDB), Department of Defense, and thereafter was revised and extended as necessary as a result of periodic reviews of the Standard by the Committee's Working Group on Telemetering, Panel on Test Range Instrumentation. The last official RDB revision of the Standards was published as RDB report MTRI 204/6 dated November 8, 1951. Since the termination of the Research and Development Board organization, the Inter-Range Instrumentation Group Steering Committee, representing the major Department of Defense missile test ranges, has assigned the task of promulgating new or revised telemetry standards to the Inter-Range Telemetry Working Group (IRTWG). This publication is intended to accomplish this purpose.

The Standards have been promulgated to further compatibility of airborne transmitting equipment and ground-receiving and data-handling equipments at missile test ranges. To this end, it is the recommendation of the Inter-Range Instrumentation Group Steering Committee that telemetry equipment at the test ranges conform to these Standards.

The quality of terminal equipment, generally, will be raised by concentration of development on a minimum number of system types. However, it is *not* intended that research should be reduced on telemetry systems that may offer substantial improvements over those described in these present standards with regard to data collection, transmission, or reduction.

It is expected that these Standards will be revised from time to time as the need arises. The section titled "Looking Ahead" at the end of these Standards describes some of the changes or additions that are being considered.

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* This document was approved October 9, 1956, by the IRIG Steering Committee and supersedes IRIG Recommendation No. 102-55 dated July 31, 1955. Copies may be obtained from the Armed Services Technical Information Agency, Knott Building, Dayton 2, Ohio.

APPENDIX I

The Standards are prepared in terms of the characteristics of the signals to be transmitted by the data links, rather than by specifying terminal equipment characteristics, in order to permit flexibility in the choice of transmitting and receiving equipment components.

I. FM/FM OR FM/PM STANDARD

A. General

These telemetry systems are of the frequency division multiplex type. That is, an rf carrier is modulated by a group of subcarriers, each of a different frequency. The subcarriers are frequency modulated in a manner determined by the intelligence it is desired to transmit. One or more of the subcarriers may be modulated by a time division multiplex scheme (commutation) in order to increase considerably the number of individual data channels available in the system. The modulation of the rf carrier may be by either of two methods: frequency modulation or phase modulation.

B. Subcarrier Bands

Eighteen standard subcarrier band center frequencies with accompanying information on frequency deviation and nominal intelligence frequency response are specified in Table I. It is intended that the standard fm/fm receiving stations at the test ranges be capable of simultaneously demodulating a minimum of any twelve of these subcarrier signals.

All test ranges presently may not have demodulating equipment for all the subcarrier bands specified in Table I. Therefore, it is important that the missile or aircraft contractor expecting to require telemetry receiving services from a test range coordinate his particular subcarrier band usage with the test range at the time he first starts to plan the telemetry transmitting system. A similar recommendation applies if the contractor desires more than twelve subcarrier signals (multiplexed on a single rf carrier) to be demodulated simultaneously.

The upper five bands, when used with a ±15 per cent frequency deviation, are listed as being "optional," and it is intended that each range provide the equipment for demodulating these optional bands as the need arises.

The nominal frequency response listed for each band is computed on a basis of maximum deviation and a deviation ratio of five, and it is intended that the standard receiving station be capable of demodulating data with these frequency responses. However, it should be remembered that the actual frequency response obtainable is dependent on many things, such as the actual deviation used, the characteristics of filters, etc. The primary reason for specifying a frequency response is to insure that elements in the receiving station, such as filters and recording oscillographs, do not limit the frequency responses shown in Table I.

Deviation ratios as low as one or less may be used, but low signal-to-noise ratios and possible increased harmonic distortion and crosstalk must be expected.

The eighteen bands were chosen to make the best use of present equipment and the frequency spectrum. There is a ratio of approximately 1.3:1 between center frequencies of adjacent bands except between 14.5 kc and 22 kc, where a larger gap was left to provide for a possible compensation tone if magnetic tape recording is used. The deviation has been kept at ±7.5 per cent for all bands, with the option of ±15 per cent deviation on the five higher bands to provide for transmission of higher-frequency data. When this option is exercised on any of these five bands, certain adjacent bands cannot be used, as listed in the second footnote to Table I.

It is very likely that certain applications will make amplitude pre-emphasis of some subcarrier signals desirable, and it is recommended, therefore, that the ground equipment should be capable of accommodating this pre-emphasized signal. A de-emphasis capability of up to 9 db per octave may be required.

C. Commutation

Commutation (time division multiplexing) may be used in one or more subcarrier bands. A nearly limitless variety of commutation schemes could be devised, but a few relatively simple methods will satisfy most telemetry needs. The specifications listed below for commutation were chosen to give a maximum flexibility consistent with presently available equipment and techniques; it is intended that, in order to limit the varieties which must be handled at test ranges, the following restrictions on commutation be observed. Certain commutation rates shall not be exceeded on each

TABLE I

Subcarrier Bands

Band	*Center Frequency (cps)*	*Lower Limit (cps)*	*Upper Limit (cps)*	*Maximum Deviation (per cent)*	*Frequency Response* (cps)*
1	400	370	430	±7.5	6.0
2	560	518	602	±7.5	8.4
3	730	675	785	±7.5	11.0
4	960	888	1032	±7.5	14.0
5	1300	1202	1398	±7.5	20.0
6	1700	1572	1828	±7.5	25.0
7	2300	2127	2473	±7.5	35.0
8	3000	2775	3225	±7.5	45.0
9	3900	3607	4193	±7.5	59.0
10	5400	4995	5805	±7.5	81.0
11	7350	6799	7901	±7.5	110.0
12	10,500	9712	11,288	±7.5	160.0
13	14,500	13,412	15,588	±7.5	220.0
14	22,000	20,350	23,650	±7.5	330.0
15	30,000	27,750	32,250	±7.5	450.0
16	40,000	37,000	43,000	±7.5	600.0
17	52,500	48,560	56,440	±7.5	790.0
18	70,000	64,750	75,250	±7.5	1050.0
A**	22,000	18,700	25,300	±15.0	660.0
B	30,000	25,500	34,500	±15.0	900.0
C	40,000	34,000	46,000	±15.0	1200.0
D	52,500	44,620	60,380	±15.0	1600.0
E	70,000	59,500	80,500	±15.0	2100.0

* Frequency response given is based on maximum deviation and a deviation ratio of five. (See text for discussion.)
** Bands A through E are optional and may be used by omitting adjacent bands as follows:

Band Used	Omit Bands
A	15 and B
B	14, 16, A, and C
C	15, 17, B, and D
D	16, 18, C, and E
E	17 and D.

Note: In the process of magnetic tape recording of the above listed subcarriers at a receiving station, provision may also be made to record a tape speed control tone and tape speed error compensation signals as specified in the Magnetic Recorder/Reproducer Standards. The speed control tone frequency is 17,000 cps. The compensation signal frequencies are 50,000 cps and 100,000 cps at tape speeds of 30 and 60 inches per second, respectively.

subcarrier; in all cases where automatic channel separation is desired, the commutated signal shall have a definite pattern and rates as described below; it is required that the standard receiving station be capable of accepting commutated data with the following specifications.

1) *Unseparated Data:* When automatic channel separation of a commutated subcarrier (decommutation) is not used, the commutated data may be recorded directly; *i.e.*, from each subcarrier demodulator the data shall appear in time sequence. Commutation rates should not exceed the values listed in Table II. These rates provide samples sufficiently long to permit optical interpretation and to maintain crosstalk at tolerable levels.

   a) *Conservative values:* The sample durations listed in the conservative value column of Table II are chosen sufficiently long so that the reading error during the last half of the sample, due to the switching transient, will not exceed approximately one-half per cent of the quiescent value. These values apply when the recording equipment is limited by a low-

TABLE II

Commutation Rates—Unseparated Data

Band	*Center Frequency (cps)*	*Sample Duration (milliseconds)*		*Commutation Rate* (samples per second)*	
		Conservative Values	*Minimum Values*	*Conservative Values*	*Minimum Values*
1	400	670.0	170.0	1.5	6.0
2	560	480.0	120.0	2.1	8.4
3	730	370.0	91.0	2.7	11.0
4	960	280.0	70.0	3.6	14.0
5	1300	210.0	51.0	4.9	20.0
6	1700	160.0	39.0	6.4	25.0
7	2300	120.0	29.0	8.6	35.0
8	3000	89.0	22.0	11.0	45.0
9	3900	68.0	17.0	15.0	59.0
10	5400	49.0	12.0	20.0	81.0
11	7350	36.0	9.1	28.0	110.0
12	10,500	25.0	6.4	39.0	160.0
13	14,500	18.0	4.6	55.0	220.0
14	22,000	12.0	3.0	83.0	330.0
15	30,000	8.9	2.2	110.0	450.0
16	40,000	6.7	1.7	150.0	600.0
17	52,500	5.1	1.3	200.0	790.0
18	70,000	3.8	0.95	260.0	1050.0
A	22,000	6.1	1.5	170.0	660.0
B	30,000	4.4	1.1	230.0	900.0
C	40,000	3.3	0.83	300.0	1200.0
D	52,500	2.5	0.63	390.0	1600.0
E	70,000	1.9	0.48	530.0	2100.0

* Frame rate times the number of samples per frame. This assumes no loss time between samples. Multiply this value by the duty cycle for the actual values.

APPENDIX I

TABLE III

Commutation Specifications for Automatic Decommutation

*No. of Samples Per Frame**	*Frame Rate (frames per second)*	*Commutation Rate*** (samples per second)*	*Lowest Recommended Subcarrier Bands (cps)*
18	5	90	14,500
18	10	180	22,000 (±15 per cent) or 30,000 (±7.5 per cent)
18	25	450	30,000 (±15 per cent) or 70,000 (±7.5 per cent)
30	2.5	75	10,500
30	5	150	22,000 (±7.5 per cent)
30	10	300	22,000 (±15 per cent) or 40,000 (±7.5 per cent)
30	20	600	40,000 (±15 per cent)
30	30	900	70,000 (±15 per cent)

* The number of samples per frame available to carry information is two less than the number indicated, because the equivalent of two samples is used in generating the frame synchronizing pulse.
** Frame rate times number of samples per frame.

pass filter whose cutoff frequency is equal to the specified frequency response of that subcarrier band as given in Table I.

b) *Minimum values:* The sample lengths listed in the minimum value column of Table II provide a sample that is one fourth the length listed in the conservative value column. These values are to be used only when higher sampling rates are essential. They may be used only when the usual low-pass filters for the deviation ratio of five have been replaced with units having cutoff frequencies about four times the recommended frequency response. The removal of the regular low-pass filter will permit the recording of a considerable amount of spurious signals. The reading accuracy of samples recorded in this manner will be considerably reduced.

2) *Separated Data:* Where required, automatic channel separation (decommutation) equipment shall be provided in the receiving station to process commutated signals that conform to the following characteristics.
   a) The total number of samples per frame (number of segments of a mechanical commutator) and the frame rates shall be one of the combinations shown in Table III. If a higher repetition rate is required for certain information, two or more samples per frame (equally spaced in time) can be used to represent one telemetered function at the expense of the total number of information channels.
   b) The commutation pattern, in the subcarrier frequency vs time domain, shall be as shown in Fig. 1.
   c) A frame synchronizing pulse of duration equal to two "on" periods plus one "off" period shall be provided once every frame, as shown in Fig.
   d) The commutator speed (or frame rate) shall not vary more than + 5 — 15 per cent from the nominal values given in Table III.

e) When airborne gating is used, the duration of each information pulse shall be within the bounds of 47 to 53 per cent of nominal channel period and shall be stable to plus or minus one half per cent of nominal channel period. It should be noted that stability of information pulse duration often affects system accuracy. Changes in the channel period due to changes in frame rate must be absorbed in the "off" time.

f) When airborne gating is not used, it may be necessary to use ground gating and the ratio of information pulse duration to nominal channel period shall be within the bounds of 60 to 75 per cent.

D. Radio Frequencies

The specifications concerning the radio-frequency carrier to be used are as follows:

1) *Radio Frequency:* 216 to 235 mc. The specific frequency assignment in this band shall be obtained by negotiation with the pertinent test range. Since up

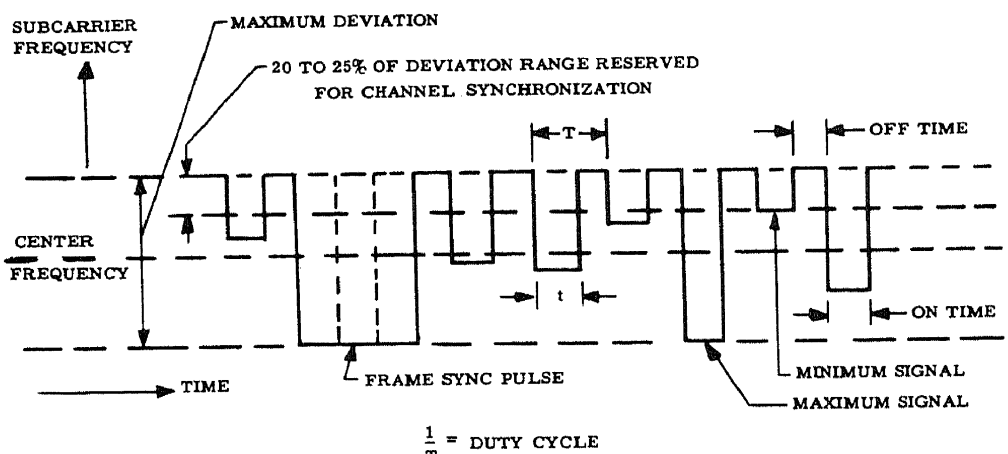

Figure 1

to approximately 0.5-mc bandwidth may be occupied by an fm/fm (or fm/pm) telemetry signal, appropriate spacing between adjacent rf channels must be provided. The extent of the guard bands required will be determined by the operating conditions existing at the individual test ranges.

2) *Stability:* The rf carrier frequency shall be stable to within plus or minus 0.2 per cent of the carrier frequency for transmitters used up to July 1, 1956. The rf carrier frequency shall be stable to within plus or minus 0.01 per cent for transmitters used after July 1, 1956.

3) *Type of Radio-Frequency Modulation:* Frequency or phase modulation.

4) *Radio-Frequency Deviation:* ±125-kc maximum (equivalent frequency deviation in the case of phase modulation). It is recommended that at least ±75 kc be used.

5) *Power:* 100-w maximum, depending on distance and propagation problems; no more should be used than necessary to achieve reliable transmission.

6) *Spurious Signal Radiation:* The radiated power of harmonics and all other spurious signals shall be 60 db, or greater, below the power level of the fundamental.

7) *Polarization:* If a circularly-polarized transmitting antenna is used on a missile or aircraft, the signal transmitted to the rear, or downward, shall be right-hand polarized (by IRE definition). Any use of circularly-polarized transmitting antennas should be coordinated in advance with the test range involved, to insure compatibility with receiving antennas.

APPENDIX I

II. PDM/FM STANDARD[1]

A. General

The pulse duration modulation (pdm) systems are intended for use where a strictly time division multiplex system can meet the bulk of the telemetry requirements of a given application. A relatively large number of information channels can be accommodated, but at a relatively low-frequency response capability in comparison with the subcarrier channels of the fm/fm system. Although the specifications to be given are based on previous experience with mechanical commutators, nothing in this Standard is intended to prevent the use of electronic commutation methods.

B. Pulse Duration Modulation Specifications

The following are the specifications for the pulse duration modulated signal.

Number of samples per frame[2]	30	45	60	90
Frame rate (frames per second)	30	20	15	10
Commutation rate (samples per second)[3]	900	900	900	900

The information being transmitted in each channel shall determine the duration of the corresponding pulses. The relation between information magnitude and pulse duration, in general, should be linear.

Minimum pulse duration (zero level information)	90 ±30 μsec
Maximum pulse duration (maximum level information)	700 ±50 μsec
Pulse rise and decay time (measured between 10 per cent and 90 per cent levels)	10 to 20 μsec (constant to ±3 μsec for a given transmitting set)

The time interval between the leading edges of successive pulses within a frame shall be uniform from interval to interval and shall be constant within plus or minus 25 μsec. This time interval shall have a nominal period equal to one divided by the total sampling rate.

The commutator speed (or frame rate) shall not vary more than plus 5 per cent to minus 15 per cent from nominal.

Frame synchronization of the receiving station shall be provided for by leaving a longer than normal time gap in the train of pulses transmitted. This gap shall be the same as that normally occupied by two successive data channel pulses. A representation of the pulse train waveform is shown in Fig. 2.

C. Radio-Frequency Carrier Specifications

The following are the specifications for the radio-frequency carrier and its modulation.

1) *Radio Frequency:* 216 to 235 mc. The specific frequency assignment in this band shall be obtained by negotiation with the pertinent test range. Because up to approximately 0.2-mc bandwidth may be occupied by a pdm/fm telemetry signal, appropriate spacing between adjacent rf channels must be provided.

[1] These systems have sometimes been designated as pwm/fm.

[2] The number of samples per frame available to carry information is two less than the number indicated becau[s]e equivalent of two samples is used in generating the frame synchronizing pulse.

[3] Commutation rate is equal to the frame rate multiplied by the number of samples per frame.

APPENDIX I

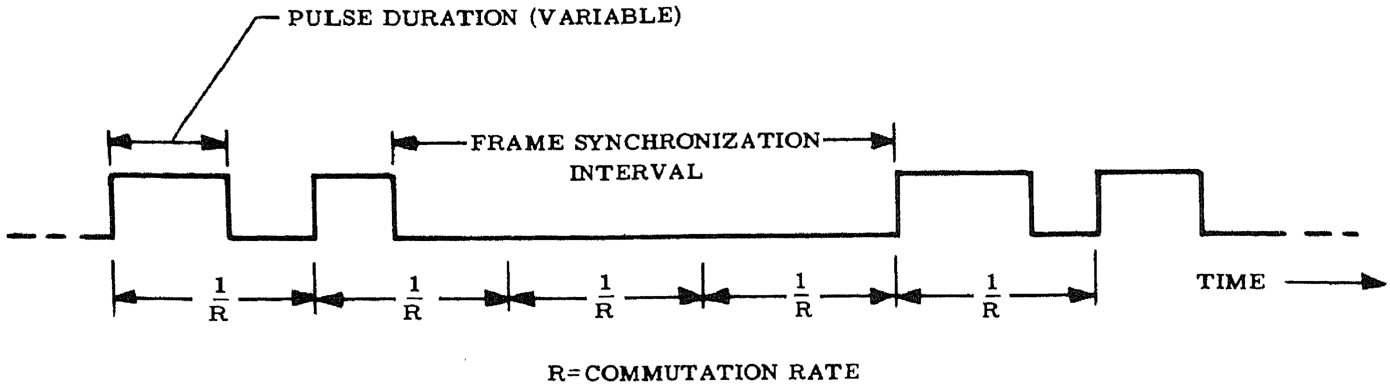

Figure 2

The extent of the guard bands required will be determined by the operating conditions existing at the individual test ranges.

2) *Stability:* The rf carrier frequency shall be stable to within plus or minus 0.01 per cent.
3) *Type of Radio-Frequency Modulation:* Frequency modulation.
4) *Radio-Frequency Deviation:* ±25 to ±45 kc.
5) *Power:* 100-w maximum, depending on distance and propagation problems; no more should be used than that necessary to achieve reliable transmission.
6) *Spurious Signal Radiation:* The radiated power of harmonics and all other spurious signals shall be 60 db, or greater, below the power level of the fundamental.
7) *Polarization:* If a circularly-polarized transmitting antenna is used on a missile or aircraft, the signal transmitted to the rear, or downward, shall be right-hande polarized (by IRE definition). Any use of circularly-polarized transmitting antennas should be coordinated in advance with the test range involved, in order to insure compatibility with receiving antennas.

LOOKING AHEAD

As stated in the Foreword, it is expected that these Standards will be revised from time to time as the need arises. Among the future changes or additions to these Standards being considered are the following.

1) Changed and/or additional rf carrier bands for telemetry usage.
2) Modulation of subcarriers of the fm/fm system with a pdm signal (pdm/fm/fm system).
3) Changes in frame rates and samples per frame in commutation standards to ease problems of data processing.
4) Direct modulation of the rf carrier by a single channel of wide-band data.
5) Additional subcarrier bands for the fm/fm system.
6) Pulse code modulation systems.

The time when changes or additions, such as those outlined above, are made will depend on need, the state of the art, and usage that is widespread enough to justify standardization.

MAGNETIC RECORDER/REPRODUCER STANDARDS*

(IRIG Document No. 101-57)

Prepared by Inter-Range Telemetry Working Group
Inter-Range Instrumentation Group
Air Force Missile Test Center
Holloman Air Development Center
Naval Air Missile Test Center
Naval Ordnance Missile Test Facility
Naval Ordnance Test Station
White Sands Proving Ground

FOREWORD

These Standards have been devised to further the compatibility of telemetry data tape recorder/reproducer devices at Department of Defense missile test ranges. Compatibility of these devices is required primarily to provide tape recorded data in a standard form to permit interchange of data records between the various facilities. The interchange of data records is a requirement whenever tests are conducted at one facility and data is reduced at another.

These Standards are based on the configuration of the majority of equipment presently in use or planned for use at the various test facilities. There is no intent of limiting or reducing the research and development effort on magnetic recording devices and techniques; rather, the intent is to set forth general configuration limits within which research and development can proceed without affecting recording system compatibility.

Although meant primarily for telemetry data recording and reproducing purposes, it is intended that these Standards also serve as a guide in the procurement of airborne magnetic recording equipment. Compatibility of airborne recording equipment is desirable, in order to utilize standard reproducing equipment on the ground for playback purposes.

Because the magnetic tape is the only common element between the record and reproduce device, configuration of these devices is referenced, where applicable, to the magnetic tape.

It is the recommendation of the Inter-Range Instrumentation Group Steering Committee that magnetic recorder/reproducer devices, for telemetry and airborne data collection applications, conform to these Standards.

* This document was approved February 14, 1957, by the IRIG Steering Committee. Copies may be obtained from the Armed Services Technical Information Agency, Knott Building, Dayton 2, Ohio.

APPENDIX II

I. SCOPE

These Standards define terminology and specify the configuration and operating characteristics of magnetic recording/reproducing devices used for telemetry and airborne data collection applications at the missile test ranges.

II. DEFINITIONS

Magnetic Recorder/Reproducer. A machine which converts electrical data signals to magnetic signals on a magnetic tape during a recording process and/or converts the magnetic signals on a magnetic tape to electrical data signals during a reproducing process. Such a device may be considered as a "black box" which introduces only a controlled time delay into the input data signals.
Magnetic Tape. The medium upon which signals are recorded and stored in a magnetic recorder/reproducer system.
Record Head. An electromagnetic transducer used during the record process for inducing magnetic fields into the tape.
Reproduce or Playback Head. An electromagnetic transducer which converts the remanent flux signals in a magnetic tape into electrical signals during the playback process.
Head Stack. A group of two or more heads mounted in a single unit for the purpose of obtaining multiple track recording or reproducing. The heads in any given head stack are arranged such that the individual head gaps lie in a straight line perpendicular to the direction of tape travel.
Track. A track is a portion of a magnetic tape whose width and position on the tape is specified. A track extends throughout the entire length of a reel of tape and always exists regardless of its state of magnetization.
Normal Record Level. Normal record level is the level of record head current required to produce 1 per cent third harmonic distortion of the reproduced signal, when the distortion is a function of magnetic tape overload and is not a function of electronic circuitry.
Maximum Record Level. Maximum record level is the level of record head current required to produce 3 per cent third harmonic distortion of the reproduced signal, when the distortion is a function of magnetic tape overload and is not a function of electronic circuitry.
Speed Control Signal. A speed control signal is an amplitude modulated signal recorded for the control of tape speed during the playback process.
Compensation Signals. A compensation signal is a signal recorded on the tape, along with the data and in the same track as the data, which is used during the playback of data to electrically correct for the effects of tape speed errors.
Timing Signals. A timing signal is any signal recorded simultaneously with data for use during playback in data reduction applications.

III. TAPE WIDTHS

The standard tape widths for all but special applications are ¼ inch, ½ inch, and 1 inch, with the tolerance on all widths being $+0.000$ inch, -0.004 inch. A tape width of ½ inch is preferred where compatible with program requirements.

APPENDIX II

IV. TAPE SPEEDS

Standard speeds for the direct recording and playback of IRIG standard telemetry als are 60 and 30 inches per second.

V. TAPE REELS

The standard magnetic tape reel sizes are 10½- and 14-inch-diameter reels. The preferred machine shall handle standard reel sizes. Dimensions and tolerances of reel flanges and hubs shall be as specified by NARTB Standards. Extensive investigations are at present underway to determine the requirements for improved tape reels and to develop adequate reels when actual requirements are known. These Standards for magnetic tape reels will be amended if and when such investigations show a change in dimensions and tolerances to be advisable.

VI. TAPE REEL POSITIONING AND CONTROL

The tape reel centering and hold-down device shall provide a reel eccentricity not to exceed 0.01 inch and shall permit no movement of the reel perpendicular to the plane of the tape transport.

VII. TAPE GUIDES

Tape guides shall be provided to maintain the tape position within ±0.005 inch, which the tape passes through the head assembly.

VIII. TRACK SPECIFICATIONS

Track Width. The track width for multiple-track recording shall be 0.050 inch ±0.005 inch. Track width is defined as the physical width of the head which would be used to record or reproduce any given track, although the actual width of the recorded track will be somewhat greater because of the magnetic fringing effect around each recording head.
Track Spacing. Tracks shall be spaced 0.070 inch center-to-center across the tape and, as a group, shall be centered on the width of the tape. Therefore, the preferred tape width (½ inch width) would contain 7 tracks, with 1 track located at the center of the tape.
Track Numbering. The tracks on a tape shall be numbered consecutively, starting with track number "one," from top to bottom when viewing the oxide-coated side of a tape with the earlier portion of the recorded signal to the observer's right.

IX. RECORD AND REPRODUCE HEAD CONFIGURATION

Head Location. The standard head placement is to locate the heads (both record and playback) for alternate tracks in separate head stacks. Thus, to record in all tracks of a standard width tape, two record head stacks will be used, and to reproduce from

all tracks of a standard width tape, two record head stacks will be used, and to reproduce from *all* tracks of a standard width tape, two playback head stacks will be used.
Head Stack Numbering. Head stack number "one" of a pair of head stacks (either record or playback) is the first stack over which an element of tape passes while moving in the normal "record" or "playback" direction.
Head Numbering. Heads, both record and playback, shall be numbered to correspond to the track on the magnetic tape which they normally record or reproduce. Stack number "one" of a pair will contain all odd numbered heads, while stack number "two" of a pair will contain all even numbered heads.
Gap Alignment. The centers of the individual head gaps in any stack shall lie within 0.0002 inch of a straight line which is perpendicular to the direction of tape travel.
Head Stack Placement. The lines of gaps in the two head stacks of a pair (either record or reproduce) shall be spaced 1.500 inches, ±0.001 inch, apart (as measured along the tape path).

X. RECORD/REPRODUCE FREQUENCY CHARACTERISTICS

The over-all frequency response characteristics of a tape recorder/reproducer are a function of the tape speed used. An instrumentation machine shall record and reproduce data with response in accordance with Table I.

TABLE I

Over-All Record/Reproduce Frequency Response Characteristics

Tape Speed (inches per second)	3 db Pass Band (cps)
60	300 - 100,000
30	300 - 50,000

The 30 inches per second tape speed response is adequate for recording IRIG fm subcarriers up to and including 30 kc and for recording IRIG standard pdm signals.

XI. RECORD AMPLIFIER CHARACTERISTICS

The record amplifier shall be designed and connected to the recording head in such a manner that the signal current in the head for constant voltage supplied to the amplifier input does not vary more than ±2 per cent over the pass bands given in Table I.

XII. REPRODUCE AMPLIFIER CHARACTERISTICS

The reproduce amplifier shall be connected to the reproduce or playback head and shall be designed to compensate (by use of suitable equalization circuitry) for magnetic-tape and record and reproduce-head characteristics in such a manner that the over-all record/reproduce frequency characteristics of Table I are obtained.

APPENDIX II

XIII. SPEED CONTROL SIGNAL

The speed control signal is an amplitude modulated signal with the following characteristics:

Subcarrier frequency	17.0 kc ±0.02 per cent
Modulating frequency	60 cps ±0.02 per cent
Percentage modulation	50 per cent ±5 per cent
Operating level	10 db, ±5 db, below normal record level.

XIV. COMPENSATION SIGNALS

Compensation signals to be used for correction of tape speed error effects are a function of tape speed as follows:

Tape Speed	Compensation Tone Frequency
30 inches per second	50 kc ± 0.01 per cent
60 inches per second	100 kc ± 0.01 per cent

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